**Title:** The role of subsidence and accommodation generation in controlling the nature of the aeolian stratigraphic record

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## Abstract

Despite a well-documented record of preserved aeolian successions from sedimentary basins characterised by widely variable subsidence rates, the relationship between aeolian architecture and subsidence-driven accommodation generation remains poorly constrained and largely unquantified. Basin subsidence as a control on aeolian sedimentary architecture is examined through analysis of 55 ancient case-studies categorised into settings of 'slow' (1–10 m/Myr), 'moderate' (10–100 m/Myr) and 'rapid' (>100 m/Myr) time-averaged subsidence rates. In rapidly subsiding basins, aeolian successions are thicker and associated with: (1) thicker and more laterally extensive dune-sets with increased foreset preservation; (2) greater proportions of wet-type interdunes and surface stabilization features; (3) more extensive interdune migration surfaces, bounding sets that climb more steeply. In slowly subsiding basins, aeolian successions are thinner, and associated with a greater proportion of (1) aeolian sandsheets; (2) supersurfaces indicative of deflation and bypass. Rapid subsidence promotes: (1) steeper bedform climb, resulting in increased preservation of the original dune foreset deposits; (2) relatively elevated water-tables, leading to sequestration of deposits beneath the erosional-baseline and encouraging development of stabilizing agents; both factors promote long-term preservation. Slow subsidence results in (1) lower angles-of-climb, associated with increased truncation of the original dune forms; (2) greater post-depositional reworking, where sediment is exposed above the erosional-baseline for protracted time. Quantitative analysis of sedimentary stratal

architecture in relation to rates of basin subsidence helps constrain the mechanisms by which sedimentary successions are accumulated and preserved into the long-term stratigraphic record.

**Supplementary Material:** Results of statistical analyses presented here are included in the supplementary information, and available at [URL to be completed when/if the submission is accepted]

**Keywords:** quantitative, stratigraphy, database, dune, climb, preservation

# Introduction

There exists a well-documented stratigraphic record of preserved aeolian deposits spanning geological time from the Archean to the present day (e.g. Clemmensen, 1985; Dott et al., 1986; Blakey et al, 1988; Voss, 2002; Cather et al., 2008; Simpson et al., 2012; Rodríguez-López et al., 2014). The mechanisms by which aeolian bedforms and related deposits are translated into the stratigraphic record are relatively well understood (Kocurek and Havholm, 1993; Kocurek, 1999). However, there have been few prior quantitative studies that demonstrate the relationship between preserved stratigraphic expression and long-term rates of basin subsidence (e.g., Howell and Mountney, 1997; Mountney et al., 1999; Mountney and Howell, 2000).

Accommodation is the space available for sediment to accumulate (Jervey, 1988). Conceptually, accommodation can be created or destroyed by fluctuations in base level – intended here as a surface of equilibrium between sediment accumulation and erosion (Catuneanu, 2006). It can be generated through basin subsidence or destroyed by surface uplift, for example. In aeolian systems, base level is represented by an equilibrium height (*sensu* Kocurek and Havholm, 1993), which defines an upper limit to which accumulation can take place. Above the equilibrium height, the airflow is capable of eroding sediment from the bed and transporting it downwind; below the equilibrium height deceleration of the airflow can lead to a rise in the level of the accumulation surface (Kocurek and Havholm, 1993, Kocurek, 1999; Kocurek and Lancaster, 1999). The long-term preservation of aeolian deposits in the geologic record requires the generation of accommodation space in which deposits can accumulate (Fig. 1). The progressive subsidence of evolving sedimentary basins is the principal mechanisms for the generation of accommodation for the accumulation of aeolian sedimentary deposits. Accumulation occurs as “net deposition through time such that a three-dimensional body of strata is formed” (Kocurek and Havholm, 1993, p. 395). However, the accumulation of aeolian sediments does not necessarily result in their long-term preservation into the geological record (e.g. Kocurek et al., 1991; Kocurek, 1999). Preservation requires a sediment accumulation to be transferred beneath the *baseline of erosion* in the long term, so that it comes to lie within the available preservation space (Fig. 1; Kocurek and Havholm, 1993; Clemmensen et al., 1994; Howell and Mountney, 1997; Kocurek, 1999). The baseline of erosion can be determined by the water-table level. In circumstances where the water table remains at a relatively constant elevation, accumulating aeolian successions may pass (‘sink’) beneath the level of the water table in response to progressive but gradual subsidence; in this way, aeolian deposits are protected from potential subsequent aeolian deflation, thereby promoting their long-term accumulation and preservation (Kocurek and Havholm, 1993; Mountney, 2012). Absolute water-table variations can occur; for example, an absolute rise can happen due to a shift to a more humid climate (Fig. 1). However, a relative rise in water table can take place even if the absolute level itself remains static: subsiding accumulated aeolian deposits may gradually sink through the static water table due to ongoing subsidence (Fig. 1; Kocurek and Havholm, 1993).

Prior research on the relationship between aeolian architecture and subsidence-driven accommodation generation has been primarily reported in the form of largely qualitative accounts, commonly for individual case studies or regions, and for aeolian successions associated with deposition in a specific basin (e.g. Clemmensen, 1987; Schenk et al., 1993; Basilici et al., 2009; Leleu and Hartley, 2010). As such, isolating and quantifying the global effects of subsidence as a control on the aeolian sedimentary record more widely, is challenging. To address this problem, this study presents the first global quantitative comparison of the relationship between basin subsidence rate and the preserved architectures of sand-dominated aeolian sedimentary successions interpreted as deposits of large-scale aeolian dune fields or ergs (*sensu* Wilson, 1973). The aeolian successions reported herein have accumulated and become preserved in basins subject to variable rates of subsidence and associated accommodation generation (Fig. 2).

The aim of this study is to quantify and explain relationships between subsidence rates and preserved aeolian sedimentary architecture at multiple scales of observation. Three principal research questions are addressed: (1) What basin conditions are most likely to facilitate the accumulation and preservation of large (i.e. thick and laterally extensive) dune sets? (2) How are the characteristics of preserved aeolian and related architectural elements affected by variations in subsidence rate? (3) Can predictive depositional models based on quantitative metrics be proposed for aeolian successions developed in basins subject to different rates of subsidence?

# Data and Methods

### The Database of Aeolian Sedimentary Architecture

This study uses a global dataset derived from 58 published data sources that detail 55 ancient aeolian successions (Fig. 2; Table 1). Analysis has been undertaken using the Database of Aeolian Sedimentary Architecture (DASA) (Cosgrove et al., 2021a, b). DASA is a relational database in which data and metadata are stored on attributes relating to a range of aeolian and related non-aeolian entities, including lithofacies and architectural elements, and bounding surfaces present in aeolian successions at various scales (Table 2). Quantitative and qualitative characteristics defining element types, geometries, spatial relationships and bounding surfaces are recorded in the database.

All case studies are associated with ancillary data describing the geological background and the boundary conditions present at the time of deposition. Such ancillary data include geological age, basin setting, prevailing climate and palaeosupercontinental setting of each case study. These data are drawn from the original source works and related published literature.

### Subsidence Histories

Each case study included in this investigation (1) is associated with accumulation in a particular sedimentary basin (or part thereof), (2) spans an interval of time over which aeolian accumulation took place, and (3) is associated with a preserved stratal succession for which the total thickness is recorded (Table 1). Rates of subsidence have been gathered from total subsidence curves available in the wider literature (Table 1); subsidence curves are corrected for compaction but are not backstripped. For descriptions of the methodologies associated with determining basin subsidence histories, refer to Allen and Allen (2013) and Lee et al. (2019). Where published subsidence curves are not available for a particular basin, accumulation rates have been used as proxies for subsidence rates; twelve such cases are included in this study (Table 1). Accumulation rates are not adjusted for decompaction. Source references from which data are derived to determine subsidence or accumulation rates are reported in Table 1.

Some case studies of aeolian successions considered in this work were originally characterized at multiple distinct geographic locations by different authors. This applies to the Jurassic Page Sandstone and Entrada Sandstone, and to the Permian Cedar Mesa Sandstone (Table 1). In these cases, rates of subsidence likely varied spatially across the large area over which these aeolian successions accumulated, for example from basin-margin to basin-centre settings. As such, these case studies have been assigned multiple rates of subsidence depending on geographic location within the basin (Table 1).

Subsidence rates have been grouped into three categories of order of magnitude: Group One comprises basin subsidence rates of >1 – ≤10 m/Myr; Group Two comprises rates of >10 – ≤100 m/Myr; Group Three comprises rates of >100 m/Myr. The chosen thresholds of subsidence rates that define these categories are arbitrarily chosen on orders of magnitude, which provides an objective way to group case studies and enables identification and discussion of evident trends. Additionally, these categories generally correspond with ranges in subsidence rates that tend to be characteristic of certain basin types (see Xie and Heller, 2009): for example, ‘rapid’ subsidence (Group Three) is common in synrift basins (e.g. Dupré et al., 2007), whereas ‘slow’ subsidence (Group One) is typical of post-rift sag basins (e.g. Castro et al., 2016).

**Limitations in Calculation of Subsidence Rate**

Ancient aeolian successions can be difficult to date in absolute terms due to a general paucity of features suitable for absolute age dating (Rodríguez-López et al., 2014). This is especially true in the ancient rock record, for which dating techniques applied routinely to the Quaternary record (e.g. radiocarbon and OSL dating) are not appropriate. Aeolian deposits closely associated with (1) extrusive volcanics, (2) fossil-bearing marine interbeds, or (3) micro-fossils present in the aeolian deposits themselves, may be assigned a geochronometric or biostratigraphic age in some cases (e.g. Jerram et al., 2000; Scherer, 2002; Petry et al., 2007). Commonly, only a relative age can be established, enabling aeolian successions to be interpreted in terms of sequence-stratigraphic or climate-stratigraphic contexts (e.g. Mountney and Howell, 2000; Atchley and Loope, 1993; Jordan and Mountney, 2010, 2012).

Many aeolian successions contain surfaces that represent and record multiple long-lived depositional hiatuses in accumulation, associated with the development of supersurfaces (e.g. Loope, 1985). For many aeolian systems, the amount of time represented by supersurfaces is likely significantly greater than that represented by the aeolian accumulations themselves; aeolian successions may be representative of only a small amount of the total geological time over which the aeolian system was active (cf. Ager, 1976; Sadler, 1981; Loope, 1985). The so-called Sadler-effect (Sadler, 1981) – i.e. the time-scale dependency of accumulation or subsidence rates – is seen to operate in the case-studies included in this investigation (see Supplementary Information). In summary, age-ranges of aeolian deposits reported in the literature may be over- or under-estimates due to (1) geochronometric errors and (2) the particular fragmentary nature of the record. The latter makes accumulation rates time-dependent; inevitably this has implications for the comparison of accumulation rates extracted from different timescales.

**Lithofacies and Architectural Elements**

Lithofacies elements are sedimentary bodies differentiated on the basis of sediment composition, texture, structure, bedding geometry, fossil content, or by the nature of their bounding surfaces (Cosgrove et al., 2021a; cf. Walker, 1984; Reading, 1986). Architectural elements are distinct sedimentary bodies with particular sedimentological properties, including characteristic internal arrangements of facies unit and external geometries (Cosgrove et al., 2021a; cf. Miall, 1985); they are the products of deposition in a specific sub-environment (e.g. a dune, a wet interdune). Lithofacies elements are contained within architectural elements (e.g. adhesion strata contained within a damp interdune); this hierarchical containment relationship is recorded (cf. Colombera et al., 2012, 2016; Cosgrove et al., 2021a, b). Non-aeolian architectural elements (e.g. elements of fluvial, sabkha, lacustrine, marine origin) are included in the database where they occur interdigitated with otherwise aeolian-dominated deposits (e.g. parts of the Permian Cutler Group; Langford and Chan, 1988).

Both architectural and lithofacies elements (see Table 2) are classified on interpretations made in the original source literature (e.g. a sandsheet at the architectural-element scale, or a stratal package of grainflow strata at the facies-element scale). The relative proportion of types of architectural elements present in different basin settings is determined based on the total number of occurrences of that particular element type. With this approach, successions that are thicker or characterized more extensively contribute more significantly to the computed proportions (cf. Cullis et al. 2019; Cosgrove et al. 2021b).

For each architectural element, internal facies distribution and external geometric properties (element thickness, length and width) are recorded. In this investigation, data on the thicknesses and lengths of architectural elements are considered. The thickness and length measurements represent the maximum observable (or recorded) thickness or length of an architectural element, as presented in an outcrop panel, for example. Lengths are recorded parallel to the overall inferred or reported direction of bedform migration. In total, 3,779 architectural elements and 721 lithofacies elements have been analysed.

**Reconstructed Dune Wavelengths and Angles-of-Climb**

Values of original dune wavelengths and angles-of-climb (reconstructed from evidence in preserved sedimentary successions) presented in this investigation include those that are stated in the original source literature. Additionally, where no values of original dune wavelengths or angles-of-climb are directly stated in the source literature, such values have been measured from architectural panels presented in the source works, where possible.

Original dune wavelengths and angles-of-climb have been reconstructed from architectural panels oriented parallel to the recorded direction of aeolian bedform migration. Dune wavelengths have been reconstructed using one of two methods: (1) by measuring the spacing of interdune elements interpreted to be the preserved record of interdune hollows that were present between coevally active and genetically related dunes; or (2) by measuring the spacing of successive interdune migration surfaces along a direction parallel to a former accumulation surface (see Mountney et al., 1999; Mountney and Howell, 2000; Fig. 1). Angles-of-climb are most reliably determined from the rise of interdune migration surfaces relative to surfaces interpreted to represent a palaeo-accumulation surface (e.g. bypass or deflationary supersurfaces, or imaginary surfaces that link multiple time-equivalent interdune hollows). Angles-of-climb have been measured using the methodologies outlined in Kocurek et al. (1991), Mountney and Howell (2000) and Mountney (2006a).

Dune wavelengths and angles-of-climb could not be determined from some datasets: (1) one-dimensional core data (e.g. Unayzah A; Melvin et al., 2010); (2) one-dimensional logs (e.g. Chugwater Formation; Taylor and Middleton, 1990); (3) outcrops oriented perpendicular to palaeo-bedform migration direction (e.g. São Sebastião Formation; Formolo Ferronatto et al., 2019); (4) outcrops lacking features indicating the attitude of a former accumulation surface (e.g. Pedra Pintada Formation; Paim and Scherer, 2007); and (5) outcrops that are limited in lateral extent (e.g. Guara Formation; Scherer and Lavina, 2005). In total, 33 dune wavelengths and 27 angles-of-climb have been determined from 15 case studies.

**Bounding Surfaces**

Types of bounding surfaces considered in detail in this investigation are (1) interdune migration surfaces and (2) supersurfaces (Kocurek, 1996; Table 2). Qualitative and quantitative data relating to these surface types are recorded (see below; Table 2).

Interdune migration surfaces are considered in context of their angle-of-climb (discussed above) and their length (i.e. lateral extent). The length of interdune migration surfaces represent the maximum recorded lengths of bounding surfaces in orientations parallel to the overall direction of bedform migration, as recorded in an outcrop panel, for example. In total, the lengths of 257 interdune migration surface have been analysed.

Qualitative data relating specifically to supersurfaces are collated. Certain supersurface types (some deflationary and stabilization surfaces) can mark the juxtaposition of separate aeolian sequences representing entirely different episodes of aeolian system construction and accumulation (e.g. Crabaugh and Kocurek, 1993). By contrast, other supersurface types (bypass and some other deflationary surfaces) record alternations between episodes of dune accumulation via positive climb, episodes of non-climbing bypass (e.g. Langford and Chan, 1988; Herries, 1993), and episodes of partial erosion through negative climb but where the same dune field remains active overall (e.g. Kocurek and Day, 2018; Mountney, 2012). Additionally, some supersurfaces can record a change in depositional environment, such as transition from aeolian to fluvial, or aeolian to marine deposition (e.g. Glennie and Buller, 1983; Chan and Kocurek, 1988; Kocurek and Havholm, 1993).

To capture the stratigraphic complexity recorded by supersurfaces, the following types of qualitative attributes of supersurfaces are considered here: (1) a classification of the environmental significance of the supersurface (i.e., whether the surface is associated with episodes of bypass or deflation, or a change in depositional environment; Table 2) according to the schemes of Fryberger (1993) and Kocurek (1996); (2) the association of sedimentary structures indicative of substrate conditions (i.e., wet, damp, dry; Table 2); and (3) the association of sedimentary structures indicative of surface stabilization (e.g. Ahlbrandt et al., 1978; Loope, 1988; Basilici et al., 2009, 2020; Dal'Bó et al., 2010; Krapovickas et al., 2016; Table 2). In total, 653 qualitative attributes relating to supersurfaces have been analysed.

**Statistical Analyses**

Both bivariate and univariate statistical analyses have been undertaken. For all bivariate analyses, the following statistics have been determined: (1) coefficient of determination ($R^2$) of power-laws; (2) Pearson correlation coefficient (R); (3) Spearman correlation coefficient (S); (4) statistical significance of the correlation coefficients (P-value). For univariate analyses, independent Group ANOVA has been used to compare the means of groups One (slowly subsiding basins), Two (moderately subsiding basins) and Three (rapidly subsiding basins). This methodology is employed to compare the means of more than two independent samples. In all statistical analyses, an $\alpha$ value of 0.05 is considered. Table 3 provides a summary of results of the statistical analyses discussed in the text; values of mean, median, standard deviation, and number of observations for variables of interest are reported, as are the results of Independent Group ANOVA statistical tests. For brevity, only mean values are reported in the text. All data used to generate the results presented below are included in full in the Supplementary Information.

# Results

### Thickness and Subsidence

Bivariate analysis reveals a statistically significant, strong positive correlation between rates of subsidence and the average thickness of aeolian successions; as rates of basin subsidence increase, the total thickness of aeolian successions tends to increase concomitantly (Fig. 3A). When values of thickness are considered for successions of slowly (Group 1), moderately (Group 2) and rapidly (Group 3) subsiding basins, the thicknesses of aeolian successions increase on average across the three groups (mean thickness = 200.01 m, 368.60 m and 916.00 m, in Groups 1, 2 and 3, respectively; Fig. 3B). There is a statistically significant difference in the average thicknesses of aeolian successions amongst Groups 1-3 (Table 3).

### Element Geometry

When all recorded aeolian architectural elements are considered together (dune-set, sandsheet and interdune elements), a statistically significant difference in aeolian architectural-element thickness is observed across the three groups (Table 3). Aeolian architectural elements have mean thicknesses of

2.68 m, 3.58 m, and 8.68 m in Groups 1 (slow subsidence), 2 (moderate subsidence), and 3 (rapid subsidence), respectively (Fig. 4A; Table 3). Specific types of aeolian architectural elements are considered next, consisting namely of dune-set, interdune, and sandsheet elements.

**Dune-Set Elements**

Bivariate analysis reveals a weak but statistically significant positive correlation between subsidence rate and the thickness of dune-sets (Fig. 5A); a significant positive correlation also exists between subsidence and the average length of dune-sets (Fig. 5B). As rates of basin subsidence increase, recorded thicknesses and lengths of dune-sets tend to increase concomitantly (Fig. 6). Dune-set elements also increase in thickness and length in a statistically significant manner across groups of basin subsidence. Mean dune-set thicknesses are 2.09 m, 4.57 m, and 9.66 m in Groups 1 (slow subsidence), 2 (moderate subsidence), and 3 (rapid subsidence), respectively (Fig. 5C; Table 3). Mean dune-set lengths are 47.04 m, 153.07 m, and 232.83 m, in Groups 1, 2 and 3, respectively (Fig. 5D; Table 3).

**Interdune Elements**

Across groups of basin subsidence, interdune elements differ in mean thickness to a statistically significant level; however, thicknesses do not vary systematically with the order of magnitude in subsidence (Group 1: interdune mean thickness = 0.60 m; Group 2: interdune mean thickness = 1.12 m; Group 3: interdune mean thickness = 0.26 m; Fig. 7A; Table 3).

Interdune thicknesses are considered according to interdune type (i.e., wet, damp and dry). Across the three groups, wet interdune types have mean thicknesses that differ to a statistically significant level (Group 1: interdune mean thickness = 0.44 m; Group 2: interdune mean thickness = 1.1 m; Group 3: interdune mean thickness = 0.25 m; Fig. 7B; Table 3). The mean thicknesses of damp and dry interdune elements do not vary significantly between the three groups (Fig. 7C, D; Table 3).

**Sandsheet Elements**

Mean values of aeolian sandsheet thickness decrease across the three groups of increasing basin subsidence rates, but these differences are not statistically significant (Group 1: mean thickness = 2.71 m; Group 2: mean thickness = 2.51 m; Group 3: mean thickness = 1.69 m; Fig. 4B; Table 3).

**Non-Aeolian Elements**

Considering only non-aeolian architectural elements, no statistically significant difference in mean values of element thickness are observed across the three groups of subsidence rates (Group 1: mean thickness = 3.40 m; Group 2: mean thickness = 2.96 m; Group 3: mean thickness = 3.77 m; Fig. 4C; Table 3).

**Relationship between Dune-Set and Interdune Elements**

Bivariate analysis of mean dune-set thickness (of each case study) versus mean interdune thickness (of each case study) shows a statistically significant positive relationship: as mean dune-set thickness increases, mean interdune thickness shows a concomitant increase (Fig. 8).

**Element Distributions**

*Architectural Elements* Aeolian elements represent 69%, 60%, and 73% of the all recorded elements in Groups 1, 2, and 3, respectively (Fig. 9A-C); the percentage of aeolian versus non-aeolian elements varies only slightly between groups. Considering aeolian architectural elements in more detail, proportions of dune-set, sandsheet and interdune elements vary between the three groups (Fig. 9D-F). Notably the proportion of dune-set elements relative to all aeolian elements increases with increasing subsidence rate; conversely, the cumulative proportions of both sandsheet and interdune elements decrease as the basin subsidence rates increase across the three groups. In Group 1, dune-set, sandsheet and interdune elements form 58%, 25%, and 17% of recorded aeolian elements, respectively (Fig. 9D); in Group 2, their proportions are 68%, 21%, and 11%, respectively (Fig. 9E); in Group 3, their proportions are 89%, 1%, and 10%, respectively (Fig. 9F).

Interdune architectural elements can be further subdivided according to type (wet, damp or dry; *sensu* Kocurek, 1981, Mountney, 2006a, b; see Table 2 for definitions). Interdune 'wetness' varies across the three groups (Fig. 9G-I). In Group 1, wet, damp, and dry interdunes form 32%, 61%, and 7% of recorded interdune types, respectively (Fig. 9G); in Group 2, they form 35%, 34%, and 31%, respectively (Fig. 9H); in Group 3, they form 92%, 8%, and 0%, respectively (Fig. 9I). Thus, greater rates of basin subsidence are associated with a greater proportion of wet interdune elements.

Non-aeolian elements form 31%, 40% and 27% of all recorded elements in Groups 1, 2, and 3, respectively (Fig. 9J-L); systematic variations with changes in the rate of basin subsidence are not seen. Across all groups of basin subsidence, non-aeolian elements are most commonly represented by alluvial and fluvial elements, which from 55%, 74%, and 90% of recorded non-aeolian element types, in Groups 1, 2 and 3, respectively (Fig. 9J-L).

**Facies Components Within Dune-Set Elements**

Across Groups 1-3, facies elements nested within dune-set architectural elements are differentiated based on the occurrence of wind-ripple strata (see Table 2 for full facies definitions). In Groups 1 and 2, facies elements composed of wind-ripple strata form 59% and 60% of recorded types within dune-set architectural elements; in Group 3 the percentage of wind-ripple-bearing facies decreases to 23% (Fig. 10).

**Bounding Surfaces**

*Surface Length* Measured surface lengths increase, on average, across the three groups of increasing basin subsidence. Mean bounding surface lengths are 70.39 m, 198.21 m, and 205.53 m, respectively, and show a significant difference between groups (Fig. 11A; Table 3).

*Supersurfaces* Deflationary supersurfaces form 53%, 45% and 35% of recorded supersurface types in Groups 1, 2, and 3, respectively (Fig. 12A-C). Bypass supersurfaces form 9%, 29% and 0% of recorded supersurface types in Groups 1, 2, and 3, respectively (Fig. 12A-C). Supersurfaces associated with a change in depositional environment form 39%, 26% and 65% of recorded supersurface types in Groups 1, 2, and 3, respectively (Fig. 12A-C).

The nature of the substrate associated with supersurfaces varies between groups of magnitude in rates of basin subsidence, but all three groups are dominantly associated with features indicative of wet surfaces; wet-type supersurfaces form 90%, 76% and 53% of all supersurfaces, in Groups 1, 2, and 3, respectively (Fig. 12D-F). When evidence for the stabilization of supersurfaces is considered, 24%, 12% and 41% of supersurfaces are classified as ‘stabilized’ (see Table 2), in Groups 1, 2, and 3, respectively (Fig. 12G-I).

**Reconstructed Angles-of-Climb and Reconstructed Dune Wavelengths**

A statistically significant positive correlation exists between subsidence rate and angle-of-climb (Fig. 13A). Angles-of-climb increase on average across the three groups of basin subsidence (0.39°, 0.54° and 1.82°, in Groups 1, 2 and 3, respectively; Fig. 11B); these differences are statistically significant (Table 3).

A moderate positive correlation exists between subsidence rate and reconstructed dune wavelengths (Fig. 13B), but only the Spearman coefficient ($S = 0.5$) is statistically significant, suggesting a non-linear relationship (Fig. 13B). Reconstructed dune wavelengths increase on average across the three groups of magnitude in rates of basin subsidence (mean dune wavelength = 140 m, 610 m, and 780 m, in Groups 1, 2 and 3, respectively; Fig. 11C), but these differences are not statistically significant (Table 3).

# Discussion

In the pre-Quaternary stratigraphic record, the preservation of the original morphological and topographic expression of aeolian dune bedforms is relatively uncommon (e.g. Clemmensen, 1988; Benan and Kocurek, 2000; Strömbäck and Howell, 2002; Scotti and Veiga, 2019); the majority of aeolian deposits are represented in the ancient stratigraphic record by cross-stratified dune-set elements, expressed as stratal accumulations produced by the migration of dunes (or larger-scale bedforms – megadunes or draa *sensu* McKee, 1979) that climbed over one another at low angles (Fig. 1). In this situation, bedform migration typically results in the preservation of only the lowermost portion of the original dunes as successive bedforms migrate over deposits left by preceding ones

(Rubin and Hunter, 1982; Rubin, 1987; Kocurek, 1991). The preserved thickness of dune-set elements arising from this so-called bedform climbing is mainly dependent on (1) the angle at which bedforms within the system climbed (Fig. 1), and (2) the original size (wavelength) of the dunes, which itself is a function of the availability and supply of sediment for aeolian dune construction, the transport capacity of the wind, and its flow behaviour (Lancaster, 1985; Lancaster, 1992; Kocurek and Lancaster, 1999; Fig. 1).The accumulation surface may be covered by aeolian dunes and interdunes in varying proportions; both can potentially climb as they migrate to leave a stratigraphic record (Fig. 1). Sand-covered surfaces that lack appreciable dune-scale bedforms can aggrade to form aeolian sandsheets (Nielson and Kocurek, 1986). Understanding how and when aeolian dune-set, interdune and sandsheet elements of different sizes and types become preserved in the long-term geological record is fundamental for interpreting the environmental significance of ancient preserved aeolian successions.

### Angle-of-Climb and Reconstructed Dune Wavelength

Directly determining accurate measurements of both angle-of-climb and original dune wavelength is not always possible using the types of architectural data recorded in some case studies (e.g. Scherer and Lavina, 2005; Paim and Scherer, 2007; Formolo Ferronatto et al., 2019). However, using a database-informed approach, it has been possible to assess – in a general way – the relationship between bedform climb angle, wavelength, and rates of basin subsidence. This is discussed in detail below.

### Angle-of-Climb

The angle-of-climb is governed by the relationship between the migration rates of bedforms and the rate of accumulation-surface rise (Kocurek and Havholm, 1993; Mountney and Thompson, 2002; Mountney, 2006a, b). Given that angles-of-climb significantly increase with increasing rates of basin subsidence (Figs. 11B and 13A; Table 3), subsidence rates can be inferred to influence either (1) the migration rate of bedforms or (2) the rate of accumulation-surface rise (Kocurek and Havholm, 1993).

The migration rates of bedforms are considered first. Although dune migration rates can be influenced by different factors (including wind intensity, the number of dunes per unit surface area, dune shape, topography, grain-size, vegetative cover, and precipitation; Bogle et al., 2015; Boulghobra, 2016; Hamdan et al., 2016; Yang et al., 2019), they are notably markedly governed by the size of the original bedform. Overall, smaller bedforms migrate more quickly than larger bedforms (Hersen et al., 2002; Groh et al., 2008). For a constant rate of accumulation-surface rise, a faster migration rate (associated with a smaller dune size) will give rise to a lower angle-of-climb (Mountney and Thompson, 2002). The results from this study indicate that the size of formative dunes – and, by proxy, dune migration rates – show no conclusive relationship with rates of basin subsidence (Figs. 11C and 13B). Hence, the significant difference in angles of bedform climb of successions in basins characterised by different rates of basin subsidence is unlikely to be primarily a function of bedform migration rates. Angles-of-climb are more likely to be influenced by the rate of accumulation-surface rise, in this context. Generation of accommodation due to a rapid rate of subsidence likely enables a faster rate of rise of the level of the accumulation surface, which allows bedforms to migrate over one another at steeper angles (Kocurek and Havholm, 1993; George and Berry, 1997; Howell and Mountney, 1997).

Evidence that angles of bedform climb are steeper in basins characterized by rapid subsidence (Group 3) is also supported by the proportion and distribution of facies within dune-set elements. Wind-ripple strata constitute a greater proportion of dune-set elements in examples from slowly subsiding basins, compared to those in rapidly subsiding basins (wind-ripple bearing facies form 59% and 23% of dune-set elements in Groups 1 and 3, respectively; Fig. 10). In aeolian dunes, wind-ripple strata are typically associated with deposition in toeset (or dune-plinth) regions (e.g. Kocurek and Dott, 1981; Mountney, 2006b; Besly et al., 2018). As such, in basins that experienced more rapid subsidence rates (Group 3), the ratio of preserved dune-foreset to dune-toeset elements is greater. Under conditions that determine higher angles-of-climb, the migration of a bedform truncates proportionately less of the foreset deposits of the preceding bedform: this results in greater preservation of steeply inclined dune-foreset deposits (characterised by dominant grainflow facies) in the successions of rapidly subsiding basins (Fig. 10).

## Reconstructed Original Dune Size

Original dune size (i.e. bedform wavelength) does not vary in a predictable way with subsidence (Figs 11C and 13B). The occurrence of thicker and longer dune sets with increasing rates of basin subsidence is therefore unlikely to reflect greater original dune sizes. Given that the size of formative dunes is primarily governed by the sediment budget of the aeolian system (Lancaster, 1985; Lancaster, 1992; Kocurek and Lancaster, 1999), this suggests that, for the case studies included in this investigation, the sediment budget is likely decoupled from basin subsidence. In the studied examples, rates of sediment supply were likely determined by allogenic forcing mechanisms that were mostly independent of controls on basin subsidence (i.e., tectonics). One key forcing mechanism is climate change (e.g. aeolian system accumulation during icehouse versus greenhouse conditions, or during glacial and interglacial conditions within a single icehouse period). The prevailing climate can markedly influence the aeolian sediment budget (Loope, 1985; Kocurek et al., 2001; Cosgrove et al., 2021b).

## Accumulation in Wet Aeolian Systems

In this investigation, increasing rates of basin subsidence are shown to be associated with increasing (1) dune-set thicknesses and (2) angles of bedform climb. Models presented in Hunter (1977), Rubin (1987) and Kocurek and Havholm (1993) suggest that increasing dune-set thicknesses and bedform migration angles should be associated with concomitant increases in the thicknesses of interbedded interdune elements (Fig. 1; Hunter, 1977; Rubin, 1987; Kocurek and Havholm, 1993). However, the results presented here do not follow this relationship; indeed interdune elements are thicker in slowly and moderately subsiding basins than in rapidly subsiding basins. Interdune elements may be expected to tend to increase in thickness with increasing rates of basin subsidence, if all interdune elements were accumulated under uniformly positive angles-of-climb (Hunter, 1977; Rubin, 1987; Kocurek and Havholm, 1993). However, in cases where the angle-of-climb is positive overall, but fluctuates at angles close to zero over shorter timescales, the accumulation and ultimate preservation of interdune elements in the stratigraphic record can be more complex (Kocurek et al., 1992; Kocurek and Havholm, 1993; Basilici et al., 2021).

Episodes where the angle-of-climb fluctuates at angles close to zero are expected to occur more frequently in moderately to slowly subsiding basins, where the generation of accommodation may be discontinuous, i.e., where aeolian accumulation is interrupted by episodes of bypass or erosion when accommodation generation ceases or stalls. This is supported by the observation that, in slowly and moderately subsiding basins, a greater proportion of deposits is delimited by supersurfaces signifying episodes of bypass and erosion, compared to rapidly subsiding basins (Fig. 12; cf. Kocurek and Havholm, 1993; Mountney and Thompson, 2002).

In slowly and moderately subsiding basins, where angles-of-climb vary (i.e. angles-of-climb fluctuate between positive and negative values), relatively thick wet and damp interdune deposits can amalgamate to form compound architectural interdune elements (Wilson, 1973; Kocurek and Havholm, 1993; Mountney and Thompson, 2002; Fig. 7B). The preservation of smaller (thinner and shorter) dune-set elements in between such amalgamated thick interdune deposits in slowly and moderately subsiding basins (Fig. 6) suggests that they originated from small isolated dune forms ('lensoidal accumulations' *sensu* Kocurek and Havholm, 1993).

**The Role of the Water-Table**

The architectures of aeolian systems are also influenced by the presence of water within the system (Kocurek, 1981; Hummel and Kocurek, 1984; Kocurek and Havholm, 1993), which can affect (1) post-depositional reworking and (2) the presence or absence of stabilizing agents (Wilson, 1973; Kocurek and Havholm, 1993; Pye and Lancaster, 2009). In rapidly subsiding basins (Group 3), elevated water-tables allow aeolian successions to be rapidly buried beneath the erosional baseline, consequently protecting the deposits from potential deflation; in part, this may contribute to the preservation of relatively thicker aeolian successions in more rapidly subsiding basins (Kocurek and Havholm, 1993; Mountney and Russell, 2009). Conversely, in more slowly subsiding basins (Group

1) relatively depressed water-tables lead to longer periods of exposure of the aeolian system above the erosional baseline, which can potentially lead to greater post-depositional reworking (Fig. 14). This is supported by the greater proportion of (1) sandsheets, which can represent remnants of eroded landforms of a higher original relief (Nielson and Kocurek, 1986; Pye and Tsoar, 1990; Mountney and Russell, 2004, 2006; Fig. 9D-F) and (2) deflationary supersurfaces in Group 1 systems; in part, this may contribute to the preservation of relatively thinner aeolian successions in more slowly subsiding basins.

Shallower (on average) water-tables in rapidly subsiding basins makes the development of damp and wet substrates more likely. These conditions may encourage the establishment of vegetation or biogenic films or crusts on aeolian substrates in some palaeoenvironmental settings (e.g. Byrne and McCann, 1989; Ruz and Allard, 1994). The presence of biogenic films and crusts and the precipitation of early diagenetic cements around plant-root structures in aeolian deposits can protect aeolian deposits from erosion through the stabilization of aeolian surfaces (Fig. 11G-I; Mountney 2006a). Stabilizing agents could further protect deposits from post-depositional deflation by inhibiting wind erosion (Fig. 14; Nielson and Kocurek, 1986; Byrne and McCann, 1989; Ruz and Allard, 1994) and reducing the mobility of river systems, which may interact with neighbouring aeolian systems and potentially erode aeolian deposits (Davies and Gibling, 2010; Almasrahy and Mountney, 2015; Reis et al., 2020; Santos et al. 2019). Fluvial elements are the most common of all the non-aeolian elements that interdigitate with aeolian elements, across all basin subsidence groups included in this study (Fig. 9J-L).

# Conclusions

This study provides the first integrated global-scale quantitative investigation into the effects of rates of accommodation generation via subsidence on aeolian sedimentary architecture. This is achieved by the examination of 55 ancient aeolian case-study successions for which data have been derived from 58 published accounts, using a database-informed approach.

Thicker and longer dune-sets are present in more rapidly subsiding basins,. principally due to accumulation associated with steeper angles-of-climb. Rapid accommodation generation and accumulation surface rise allow bedforms to climb over one another at higher angles. Facies distributions within dune-sets are related to steeper angles-of-climb in basins with higher rates of subsidence. A greater portion of grainflow facies (dune foreset deposits) are preserved relative to wind-ripple bearing facies (dune toeset deposits) in dune-sets forming parts of successions in more rapidly subsiding basins. A greater proportion of the original bedform is preserved through a steeper angle of bedform climb (Fig. 14).

Wet interdunes are more common in more rapidly subsiding basins due to relatively more elevated water tables in such settings. Rapid subsidence drives burial of aeolian deposits beneath the water table (Fig. 14). Rapid sequestration beneath relatively elevated water tables protects aeolian deposits from post-depositional deflation in more rapidly subsiding basins (Fig. 14). Greater post-depositional reworking in more slowly subsiding basins is indicated by the greater occurrence of deflationary supersurfaces and sandsheet elements in such settings (Fig. 14B).

Wet aeolian systems are less common in more slowly subsiding basins. Such depositional systems are also more likely to be ‘non-climbing’ or climbing at angles that fluctuate between slightly net positive and negative angles. As a consequence, amalgamated interdune-elements are accumulated into the sedimentary record. In wet aeolian systems, ‘non-climbing’ deposition is recorded by a greater proportion of bypass supersurfaces, associated with significant episodes of non-deposition and slower rates of overall water-table-controlled preservation-space generation. Episodes of fluctuation between non-climbing and periods of accumulation associated with low but positive angles of climb result in the preservation of thin sets of dune strata within and between relatively thicker interdune elements reflecting amalgamated (i.e. compound) wet interdune deposits.

Results arising from this work help constrain the primary controls that govern the accumulation of aeolian systems and the long-term preservation of their deposits. Results are of value in developing idealized aeolian facies models based on the most likely association of aeolian and associated non-aeolian architectural elements, deposited under variable rates of basin subsidence. As such, subsidence rates can be used to make quantitative predictions of expected aeolian facies architectures where detailed information on sedimentary architecture is not directly available, for example in non-cored subsurface aeolian successions.

## Acknowledgements

We thank the sponsors and partners of FRG-ERG-SMRG for financial support for this research: AkerBP, Areva (now Orano), BHPBilliton, Cairn India (Vedanta), Chevron, ConocoPhillips, CNOOC, Equinor, Murphy Oil, Occidental, Petrotechnical Data Systems, Saudi Aramco, Shell, Tullow Oil, Woodside and YPF. We thank reviewers Agustín Arguello Scotti and Alfonsina Tripaldi for their comments, which helped improve the paper.

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# Figure Captions

1. Definitions of terms and concepts used in this study; all sections are oriented parallel to aeolian bedform migration direction. A) Definition of angle-of-climb, dune wavelength and

dune-set thickness. The difference between dune wavelength and dune spacing is shown in Part F (dune spacing is dune wavelength plus the width of any interdune flat). B-E) Definition of accumulation and preservation space for dry and wet dry aeolian systems in overfilled and underfilled basins: B) dry system with accumulation above preservation space (overfilled); C) dry system with unfilled accumulation and preservation space (underfilled); D) wet system with no unfilled accumulation and preservation space; E) wet system with unfilled accumulation and preservation space. F-H) For dunes and interdunes of a fixed size (i.e. dune wavelength, interdune width, which together define bedform spacing), accumulated dune-set and interdune element thickness increases as the angle of climb increases. F) High angle-of-climb; G) low angle-of-climb; H) zero angle-of-climb; note that the basin fill in this case is genetically unrelated to the actively migrating but non-climbing dunes and interdunes. I-K) Preservation of dune-set and interdune elements by relative rises in the level of the water-table. L) Preservation of dune-set and interdune elements by absolute rises in the level of the water-table. Adapted in part from Kocurek and Havholm (1993).

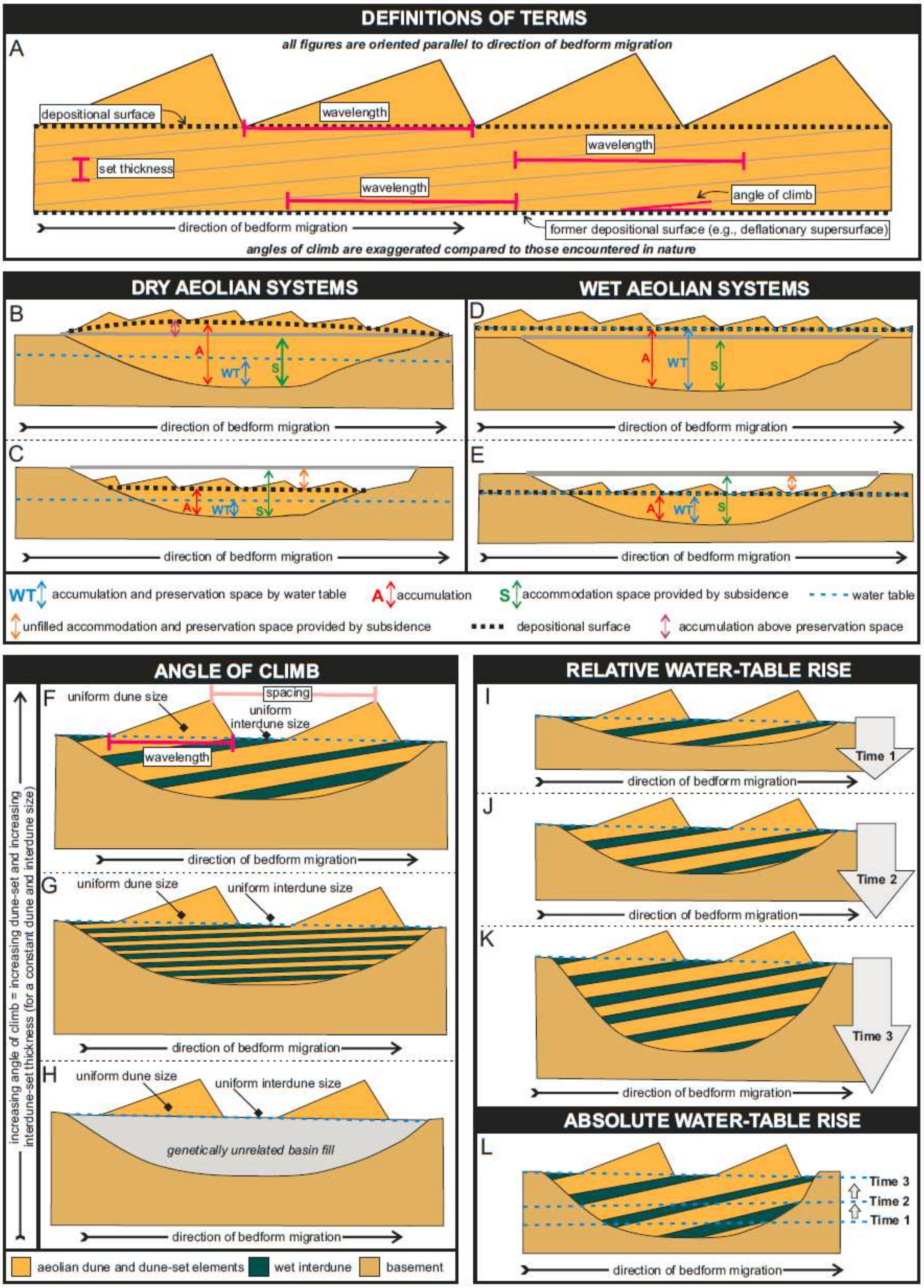
2. World map showing the geographic distribution of 55 case-studies used in this investigation. Case studies are coloured according to categories of rates of basin subsidence.
3. A) Relationship between average thickness of aeolian successions and associated subsidence rates (R = Pearson correlation coefficient; S = Spearman's correlation coefficient; P-value = statistical significance; these abbreviations apply to all scatter plots throughout this work). See Table 1 for values of thickness and subsidence rate. B) Average thickness of aeolian successions by assigned group: Group 1 (slowly subsiding basins); Group 2 (moderately subsiding basins); Group 3 (rapidly subsiding basins). The inset in Part B is the legend for box and whisker plots and applies to all such plots throughout this work.
4. Architectural element thicknesses in Group 1 (slowly subsiding basins), Group 2 (moderately subsiding basins), and Group 3 (rapidly subsiding basins). A) All aeolian architectural elements (dune-set, sandsheet, interdune); B) all sandsheet elements; C) all non-aeolian architectural elements (e.g. interdigitating fluvial, lacustrine, marine elements).

5. Relationship between the architecture of aeolian dune elements and subsidence rate. A) Dune-set thickness and subsidence rate; B) relationship between dune-set length and subsidence rate; C) dune-set thickness by assigned group: Group 1 (slowly subsiding basins); Group 2 (moderately subsiding basins); Group 3 (rapidly subsiding basins); D) dune-set length by assigned group. For all recorded lengths throughout this work true length, partial lengths, and unlimited lengths are recorded (cf. Geehan and Underwood, 1993).
6. Relationship between dune-set element thickness and length for successions related to three groups of subsidence. Refer to Table 3 for mean and median values.
7. Thicknesses of A) all interdunes, B) wet interdunes, C) damp interdunes and D) dry interdunes subdivided according to rates of basin subsidence: Group 1 (slowly subsiding basins), Group 2 (moderately subsiding basins), and Group 3 (rapidly subsiding basins).
8. Relationship between mean dune-set thickness (per case study) and mean interdune thickness (per case study).
9. A-C) Proportion of aeolian and interdigitating non-aeolian elements subdivided according to subsidence rates; D-F) proportion of aeolian element types; G-I) proportion of interdune element types (wet, damp, dry; *sensu* Kocurek, 1981, Mountney, 2006a); J-L) proportion of non-aeolian element types. All percentages are determined based on the total element count.
10. Proportion of dune foreset (combined grainfall and grainflow facies) and dune toeset (wind-ripple facies) stratal packages in dune-set elements, subdivided according to rates of basin subsidence: Group 1 (slowly subsiding basins), Group 2 (moderately subsiding basins), and Group 3 (rapidly subsiding basins).
11. A) Lengths of all recorded interdune migration bounding surfaces; B) angle-of-climb (as determined by case-study authors and measured where possible); C) reconstructed original dune wavelength (as determined by case-study authors and measured where possible). All values have been subdivided according to rates of basin subsidence: Group 1 (slowly subsiding basins), Group 2 (moderately subsiding basins), and Group 3 (rapidly subsiding basins).

12. A-C) Proportion of recorded supersurfaces subdivided according to type (deflationary, bypass, change in environment); D-F) proportion of supersurfaces associated with sedimentary features indicative of a particular surface wetness (wet, damp, dry); G-I) proportion of supersurfaces preserving evidence of surface stabilization (unstabilized, stabilized). For definitions of all supersurface types see Table 2.
13. Relationship between subsidence rate and A) angle of climb and B) reconstructed dune wavelength. Note that in Group 3, some exceptionally large angles-of-climb (> 2º) are associated with the Etjo Formation, in which a large aeolian bedform is interpreted to have migrated into a pre-existing topographic depression (see Mountney and Howell, 2000).
14. Conceptual end-member models of climbing aeolian systems deposited in basins characterized by (A) rapid and (B) slow rates of basin subsidence.

## Table Captions

1) List of the case studies used in this investigation. The geographic location of each case study is outlined in Figure 1 (identified via the case number). Each case-study is associated with an average thickness. Each case-study is associated with a rate of basin subsidence and is assigned to a group according to this rate: Group 1 (slowly subsiding basins; >1 - ≤10 m/Myr), Group 2 (moderately subsiding basins; >10 - ≤100 m/Myr), and Group 3 (rapidly subsiding basins > 100 m/Myr). The references used to calculate rates of basin subsidence are listed. The asterisk indicates that subsidence rates have been calculated from accumulation rates.
2) Definitions of aeolian and non-aeolian architectural elements, dune-set facies elements, and aeolian bounding surface types discussed in the text.
3) Results of statistical analysis. All results are grouped by subsidence rate: Group 1 (slowly subsiding basins; >1 - ≤10 m/Myr), Group 2 (moderately subsiding basins; >10 - ≤100 m/Myr), and Group 3 (rapidly subsiding basins > 100 m/Myr).

1247 


1248 *Figure 1*

1249

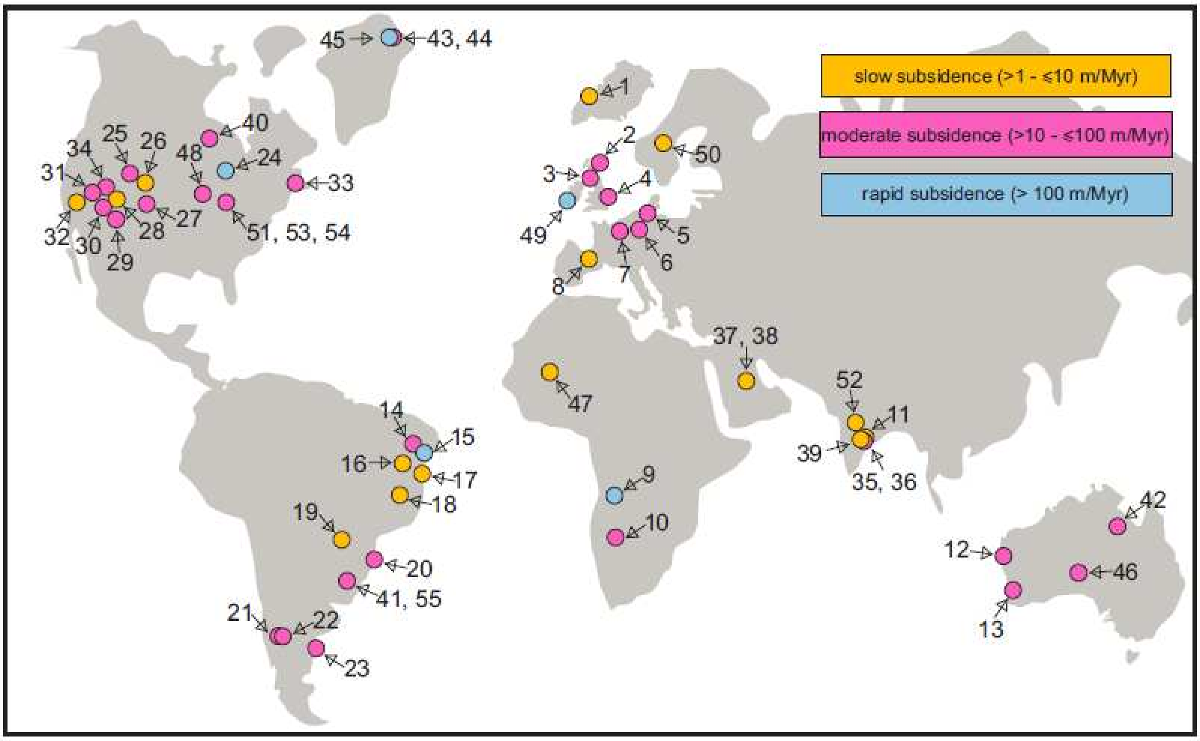



*Figure 2*

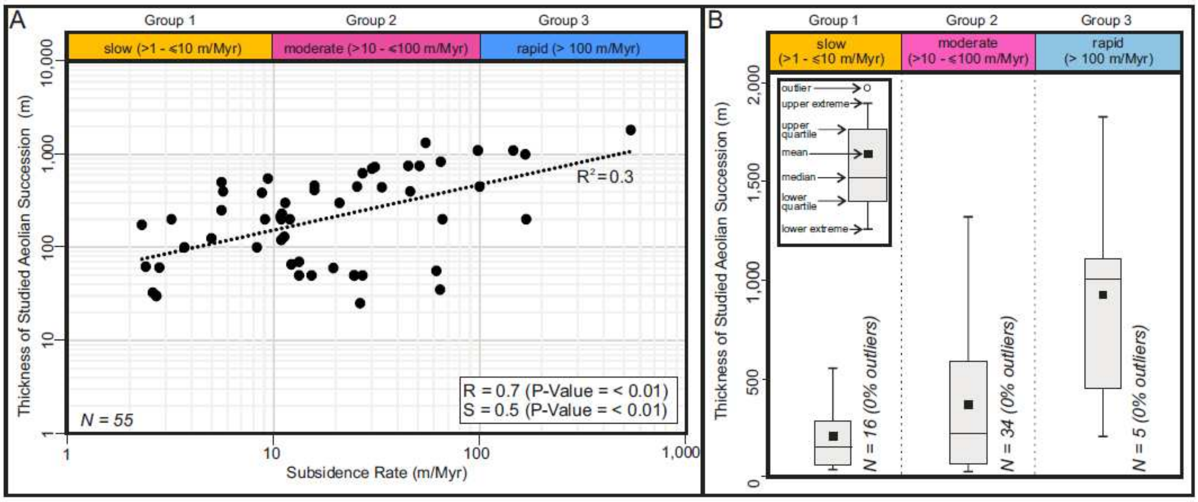



*Figure 3*

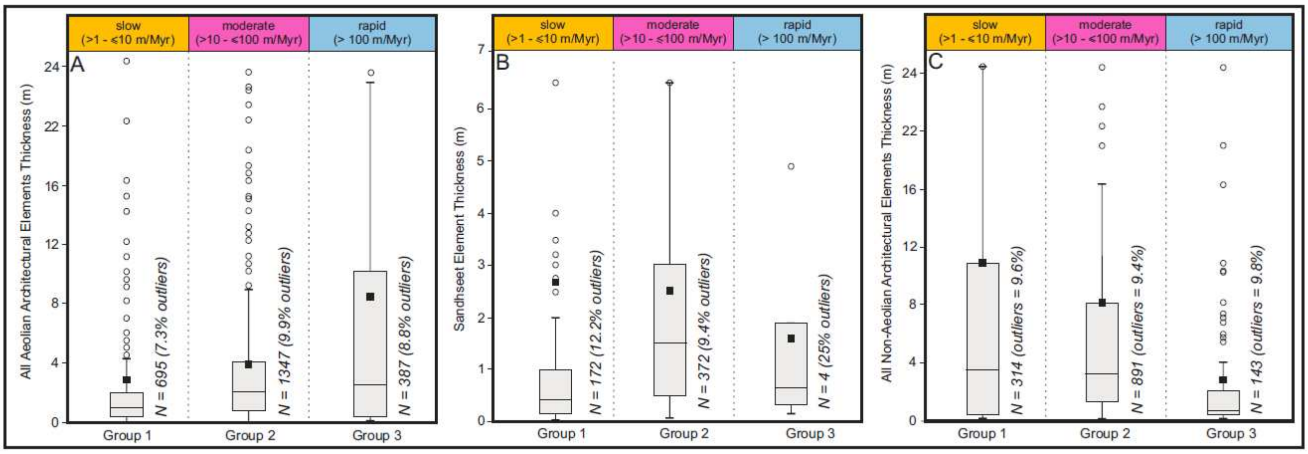



*Figure 4*

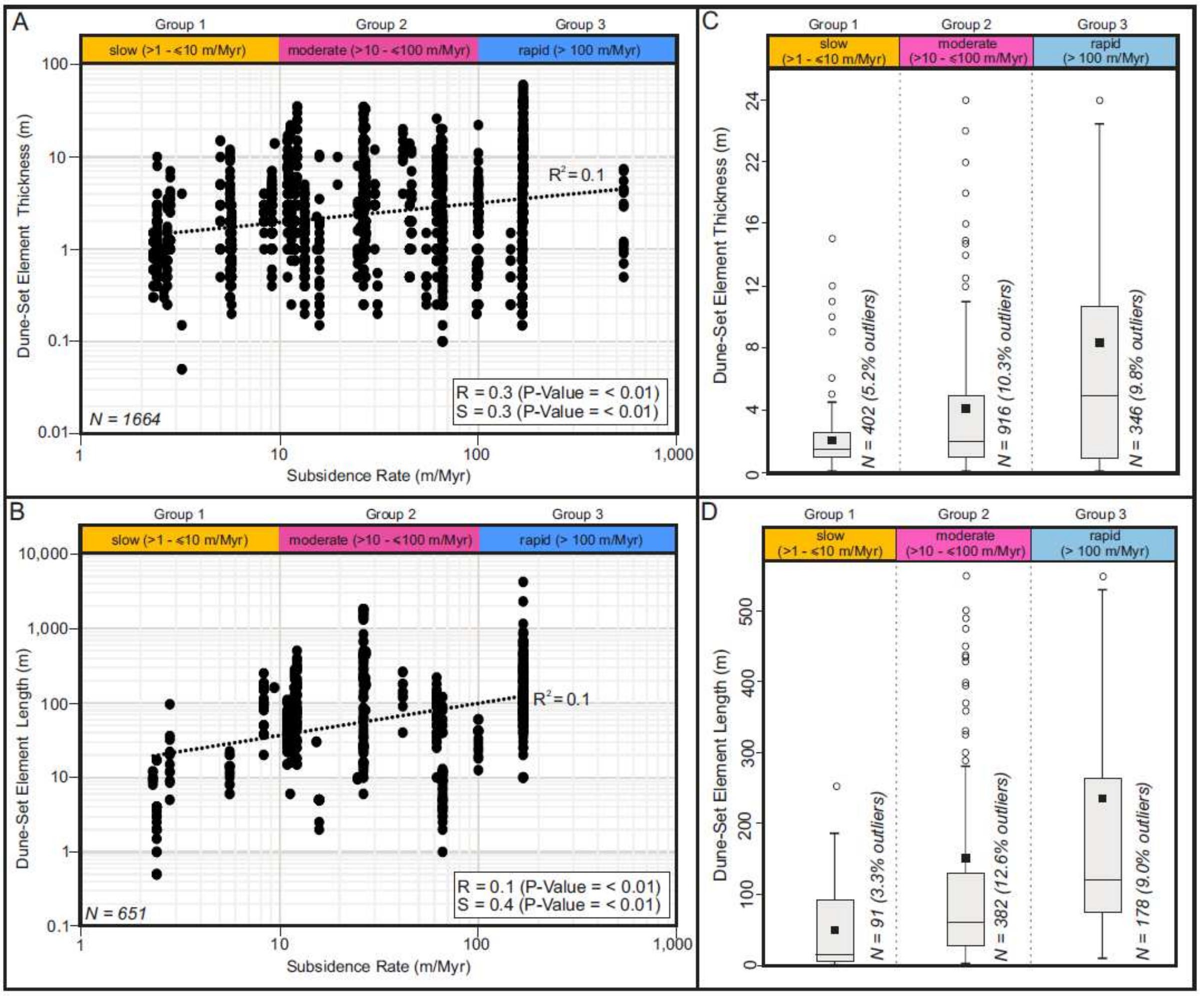



*Figure 5*

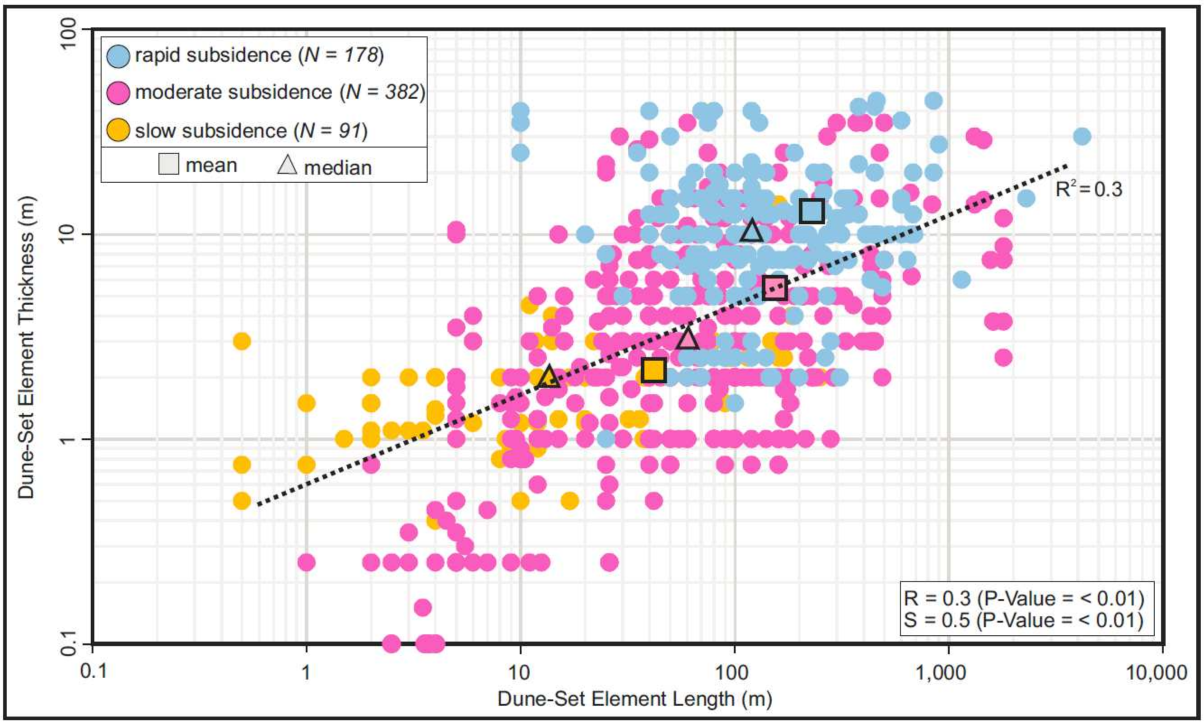

rapid subsidence (N = 178)
moderate subsidence (N = 382)
slow subsidence (N = 91)
mean
median
R² = 0.3
R = 0.3 (P-Value = < 0.01)
S = 0.5 (P-Value = < 0.01)
Dune-Set Element Thickness (m)
Dune-Set Element Length (m)
0.1
1
10
100
1,000
10,000

*Figure 6*

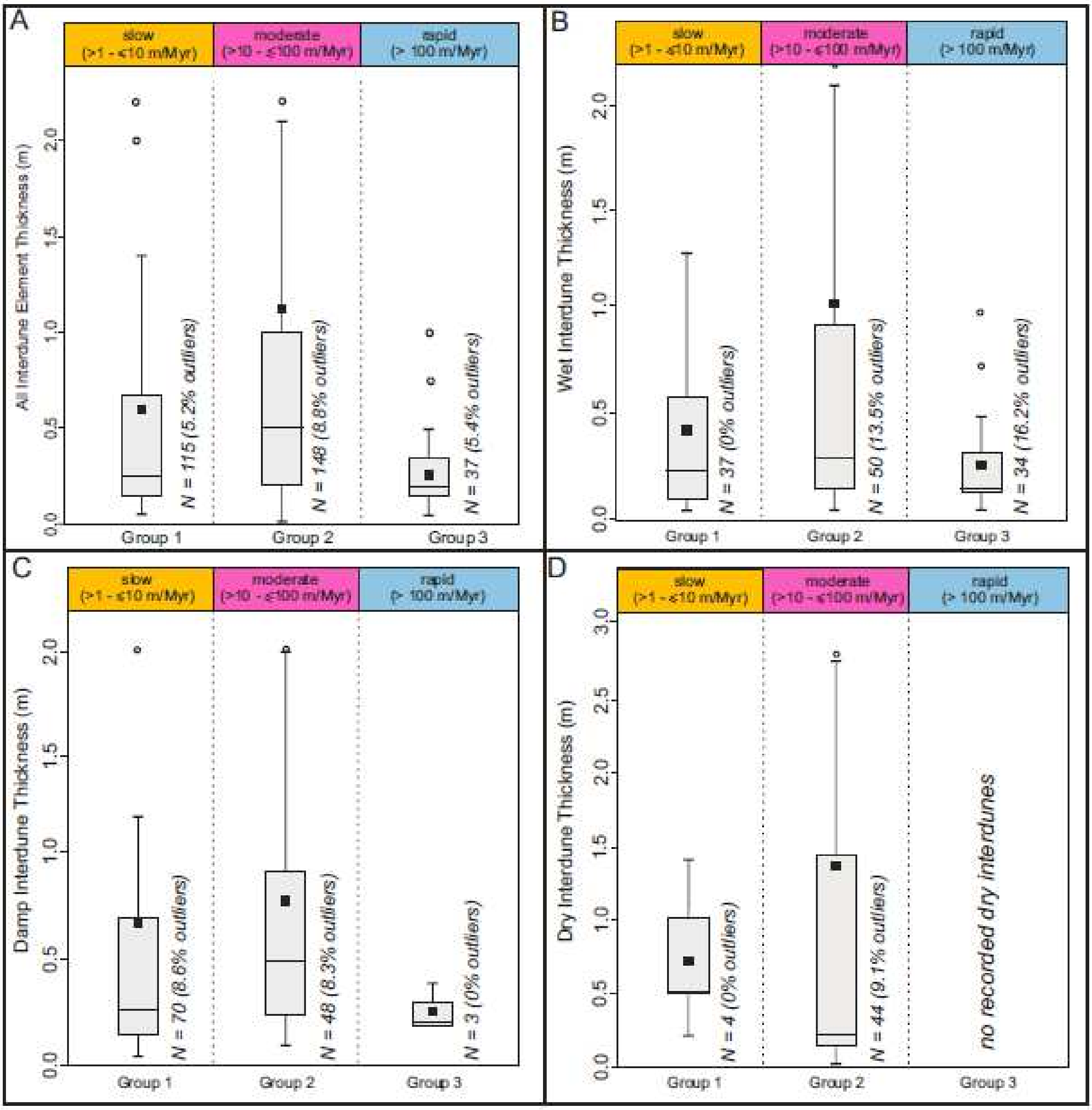

A
slow (>1 - ≤10 m/Myr)
moderate (>10 - ≤100 m/Myr)
rapid (> 100 m/Myr)
All Interdune Element Thickness (m)
N = 115 (5.2% outliers)
N = 148 (8.8% outliers)
N = 37 (5.4% outliers)
Group 1
Group 2
Group 3
B
slow (>1 - ≤10 m/Myr)
moderate (>10 - ≤100 m/Myr)
rapid (> 100 m/Myr)
Wet Interdune Thickness (m)
N = 37 (0% outliers)
N = 50 (13.5% outliers)
N = 34 (16.2% outliers)
Group 1
Group 2
Group 3
C
slow (>1 - ≤10 m/Myr)
moderate (>10 - ≤100 m/Myr)
rapid (> 100 m/Myr)
Damp Interdune Thickness (m)
N = 70 (8.6% outliers)
N = 48 (8.3% outliers)
N = 3 (0% outliers)
Group 1
Group 2
Group 3
D
slow (>1 - ≤10 m/Myr)
moderate (>10 - ≤100 m/Myr)
rapid (> 100 m/Myr)
Dry Interdune Thickness (m)
N = 4 (0% outliers)
N = 44 (9.1% outliers)
no recorded dry interdunes
Group 1
Group 2
Group 3

*Figure 7*

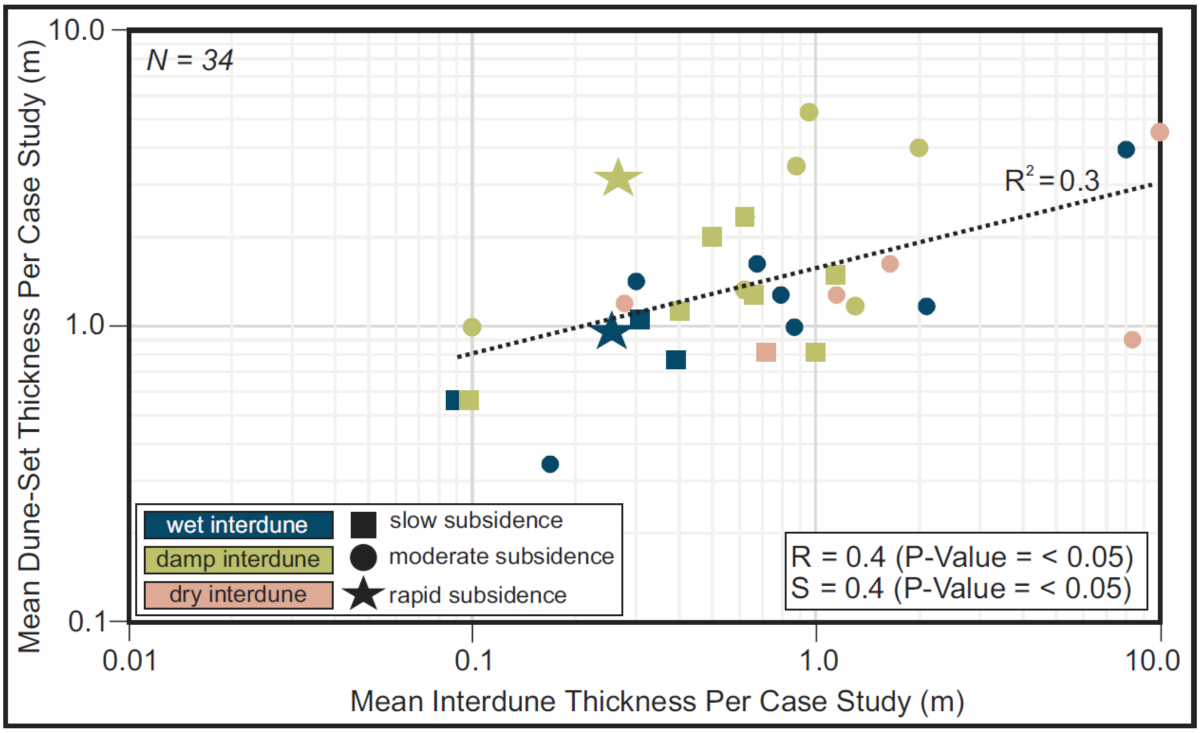

N = 34
R² = 0.3
wet interdune
damp interdune
dry interdune
slow subsidence
moderate subsidence
rapid subsidence
R = 0.4 (P-Value = < 0.05)
S = 0.4 (P-Value = < 0.05)
10.0
1.0
0.1
0.01
0.1
1.0
10.0
Mean Dune-Set Thickness Per Case Study (m)
Mean Interdune Thickness Per Case Study (m)

*Figure 8*

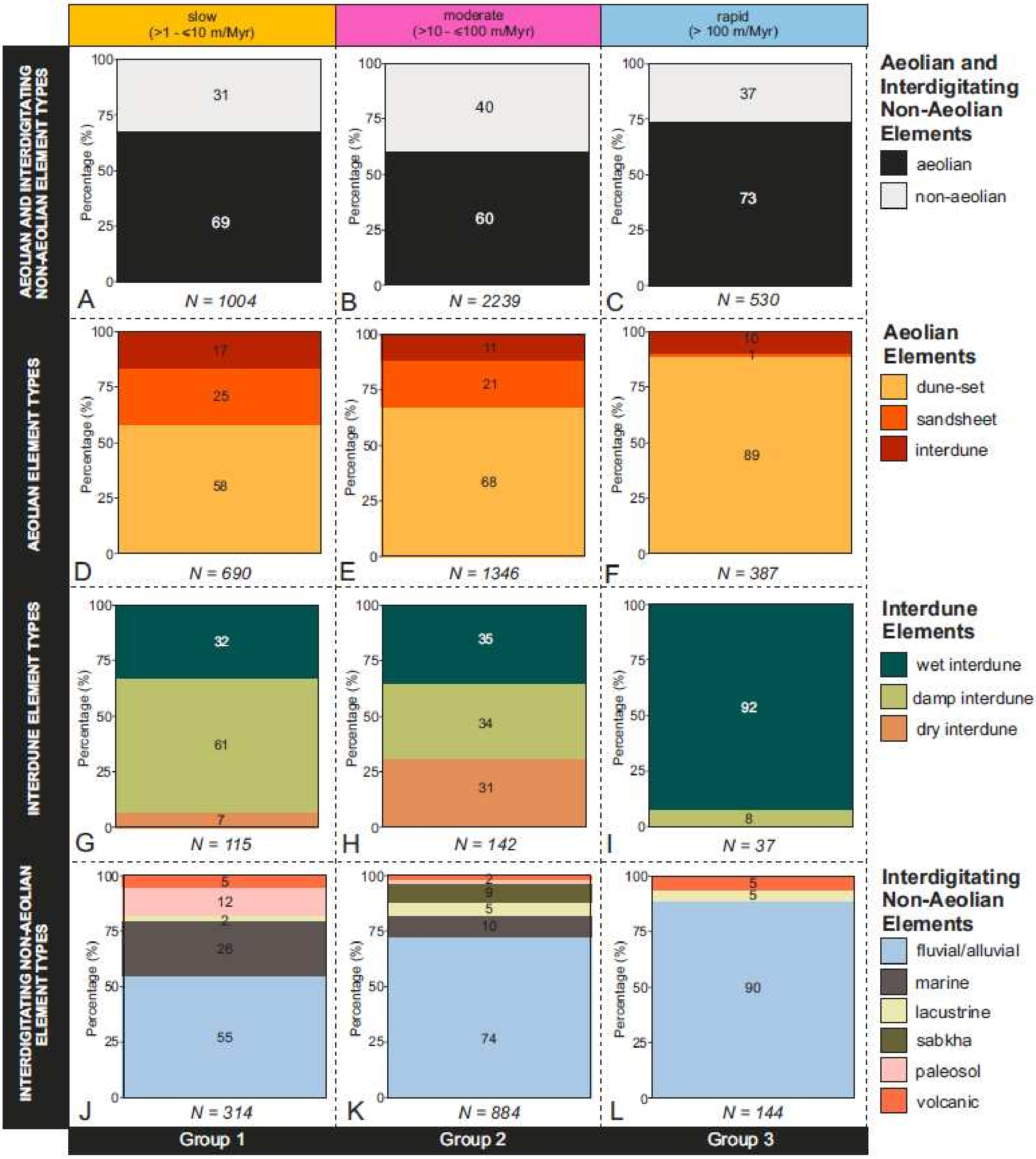

slow
(>1 - ≤10 m/Myr)
moderate
(>10 - ≤100 m/Myr)
rapid
(> 100 m/Myr)
AEOLIAN AND INTERDIGITATING NON-AEOLIAN ELEMENT TYPES
AEOLIAN ELEMENT TYPES
INTERDUNE ELEMENT TYPES
INTERDIGITATING NON-AEOLIAN ELEMENT TYPES
Percentage (%)
A
N = 1004
B
N = 2239
C
N = 530
D
N = 690
E
N = 1346
F
N = 387
G
N = 115
H
N = 142
I
N = 37
J
N = 314
K
N = 884
L
N = 144
Group 1
Group 2
Group 3
Aeolian and Interdigitating Non-Aeolian Elements
aeolian
non-aeolian
Aeolian Elements
dune-set
sandsheet
interdune
Interdune Elements
wet interdune
damp interdune
dry interdune
Interdigitating Non-Aeolian Elements
fluvial/alluvial
marine
lacustrine
sabkha
paleosol
volcanic

*Figure 9*

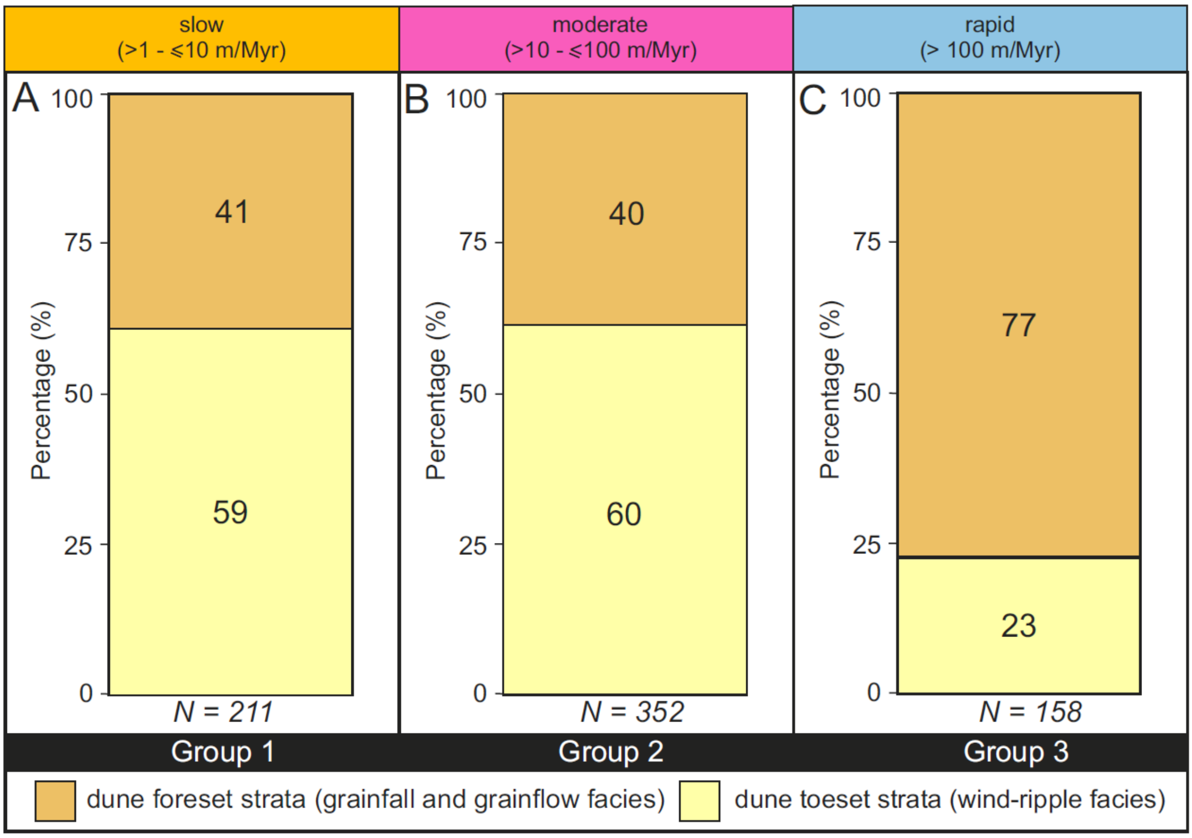



*Figure 10*

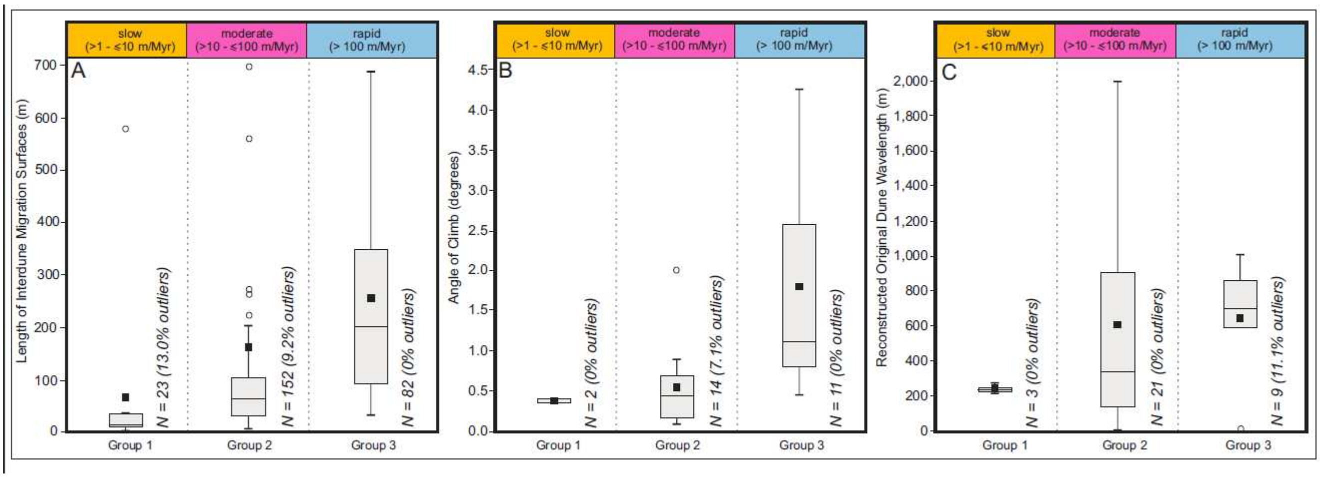



*Figure 11*

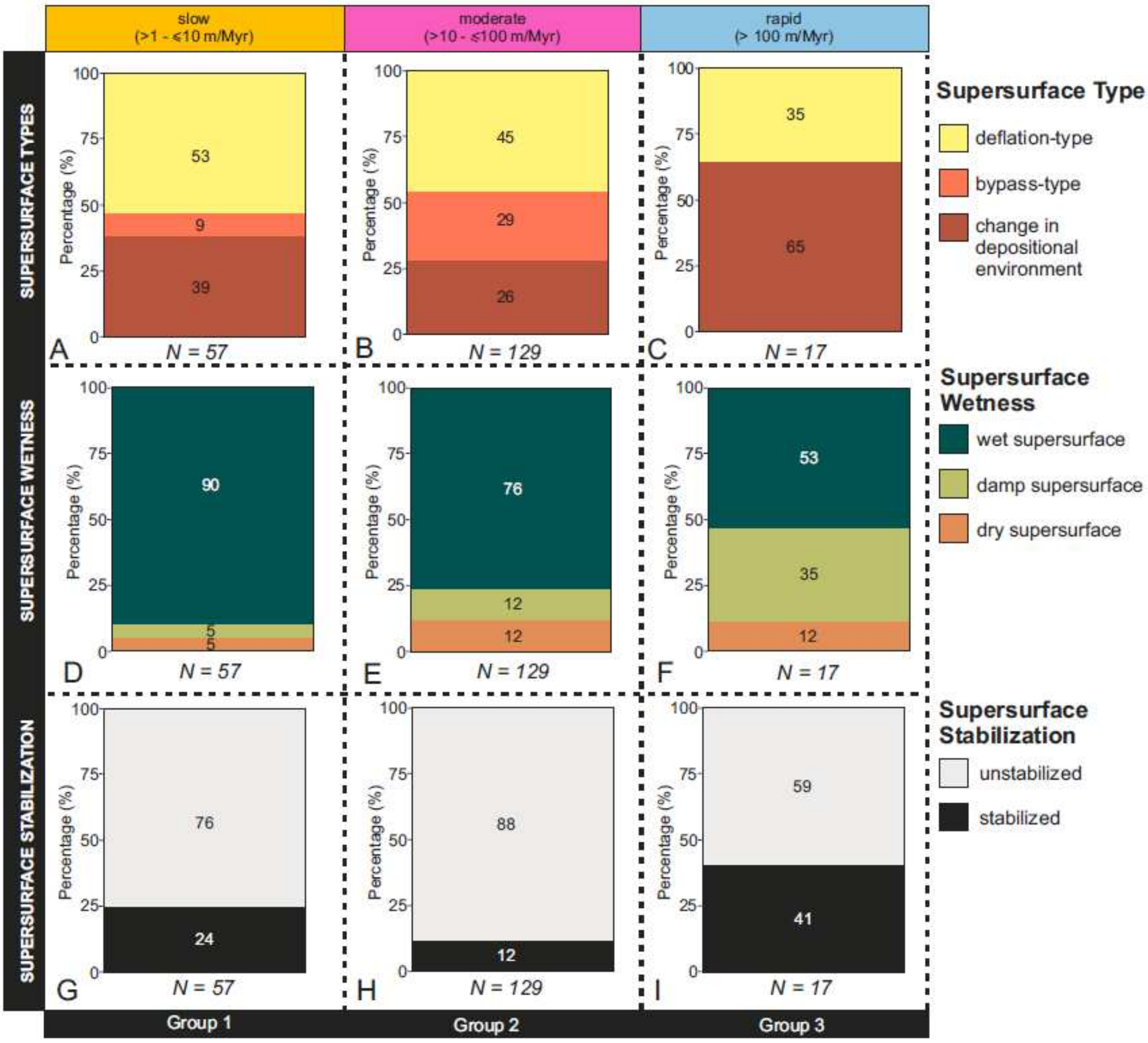



*Figure 12*

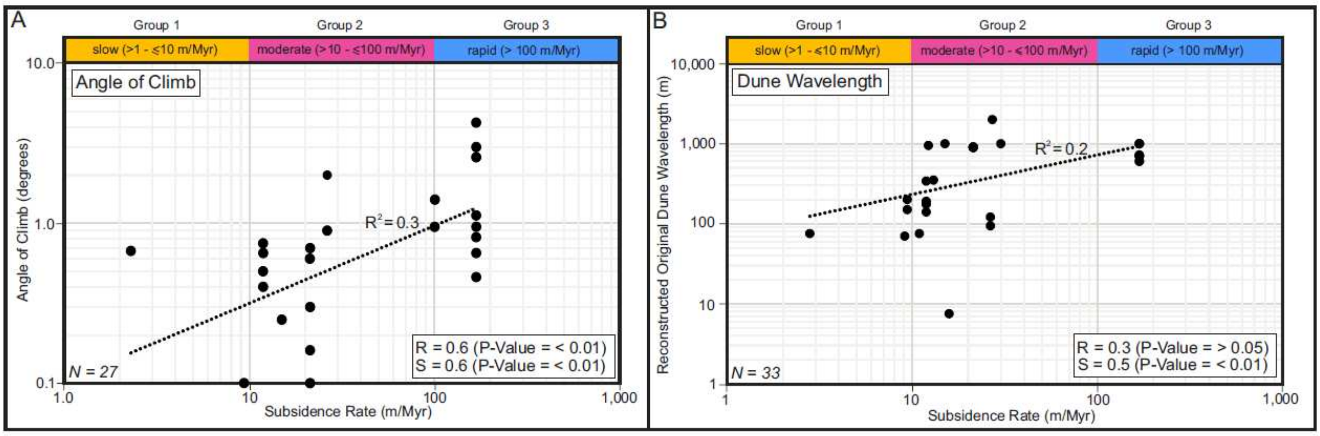
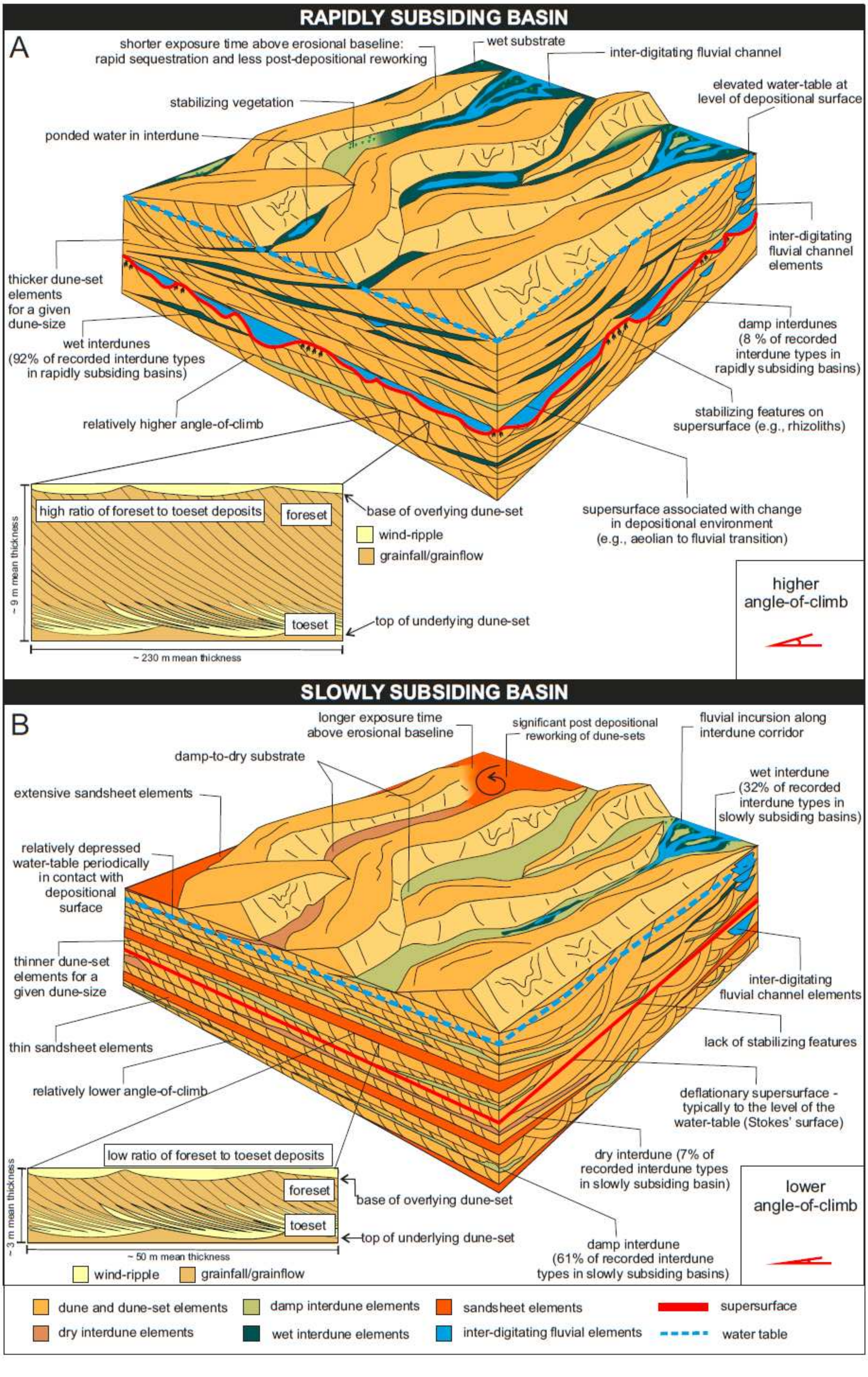



*Figure 13*

1284




1285 *Figure 14*

| Case Number | Case Study Name | Location | Source Reference(s) | Average Thickness (m) | Basin Subsidence Rate (m/Myr) | Subsidence Group | Subsidence Rate References |
|---|---|---|---|---|---|---|---|
| 1 | Eriksfjord Formation | Greenland | Clemmenesen (1988); Tirsgaard and Øxnevad (1998) | 550 | 9.4* | 1 | Clemmenesen (1988); Tirsgaard and Øxnevad (1998) |
| 2 | Hopeman Sandstone | Scotland, UK | Clemmensen (1987) | 66 | 12.2 | 2 | Argent et al. (2002) |
| 3 | Arran Red Beds | Isle of Arran, Scotland, UK | Clemmensen and Abrahamsen (1983) | 460 | 15.8 | 2 | Argent et al. (2002) |
| 4 | Sherwood Sandstone | UK (Onshore and Offshore England) | Cowan (1993); Meadows and Beach (1993) | 45 | 45.0 | 2 | Evans et al. (1993) |
| 5 | Rotliegendes Sandstone | Germany, Poland, Denmark, Baltic Sea, Netherlands | Ellis (1993); Newell (2001) | 412 | 15.8 | 2 | Van Wees et al. (2000) |
| 6 | Boxtel Formation | Netherlands | Schokker and Koster (2004) | 35 | 64.3 | 2 | Geluk et al. (1994) |
| 7 | Sables de Fontainbleau Formation | France | Cojan and Thiry (1992) | 60 | 19.5 | 2 | Prijac et al. (2000) |
| 8 | Escorihuela Formation | NE Spain | Liesa et al. (2016) | 33 | 2.6 | 1 | Vargas et al. (2009) |
| 9 | Etjo Formation | Namibia | Mountney and Howell (2000) | 200 | 168.0 | 3 | Schmidt (2004) |
| 10 | Tsondab Sandstone | Namibia | Kocurek et al. (1999) | 130 | 11.3 | 2 | Schmidt (2004) |
| 11 | Egalapenta Formation | India | Biswas (2005); Dasgupta et al. (2005) | 400 | 5.7* | 1 | Biswas (2005); Dasgupta et al. (2005); Basu et al. (2017) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 12 | Tumblagooda Formation | Australia | Trewin (1993) | 731 | 31.0 | 2 | Ghori et al. (2005) |
| 13 | Tamala Limestone | Australia | Semeniuk and Glassford (1988) | 150 | 41.6 | 2 | Falvey and Deighton (1982) |
| 14 | São Sebastião Formation | Brazil | Formola Ferronatto et al. (2019) | 200 | 66.0 | 2 | Chang et al (1992) |
| 15 | Sergi Formation | Brazil | Scherer et al. (2007) | 450 | 100.5 | 3 | Sales et al. (2004) |
| 16 | Mangabeira Formation | Brazil | Ballico et al. (2017) | 500 | 5.6* | 1 | Martins-Neto (2004); Guadagnin et al. (2015) |
| 17 | Caldeirao Formation | Brazil | Jones et al. (2015) | 62 | 2.4* | 1 | Jones et al. (2015) |
| 18 | Bandeirinha Formation | Brazil | Simplicio and Basilici (2015) | 250 | 5.6* | 1 | Martins-Neto (2004); Guadagnin et al. (2015) |
| 19 | Guara Formation | Brazil | Scherer and Lavina (2005) | 61 | 2.8 | 1 | Oliveira (1987) |
| 20 | Piramboia Formation | Brazil | Dias and Scherer (2008) | 400 | 46.0 | 2 | Oliveira (1987) |
| 21 | Huitrin Formation | Argentina | Strömbäck et al. (2005) | 50 | 27.0 | 2 | Manceda and Figueroa (1995) |
| 22 | Agrio Formation | Argentina | Viega et al. (2002) | 625 | 27.0 | 2 | Manceda and Figueroa (1995) |
| 23 | Rio Negro Formation | Argentina | Zavala and Frieje (2001) | 50 | 15.3 | 2 | Fuentes and Horton (2020) |
| 24 | Copper Habor Formation | Michigan, USA | Taylor and Middleton (1990) | 1830 | 540.0 | 3 | Cannon (1993) |
| 25 | Chugwater Formation | Wyoming, USA | Irmen and Vondra (2000) | 300 | 11.4 | 2 | Dyman and Condon (2005) |
| 26 | Arikaree Formation | Wyoming, USA | Bart (1977) | 100 | 8.3 | 1 | Still (2003) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 27 | Ingleside Formation | Colorado, Wyoming, USA | Pike and Sweet (2018) | 230 | 11.0 | 2 | Dyman and Condon (2005) |
| 28 | Lower Cutler Beds | Utah, USA | Jordan and Mountney (2010); Wakefield and Mountney (2013) | 200 | 9.1 | 1 | Nuccio and Condon (1996) |
| 29 | Cedar Mesa Sandstone (a) | Utah, USA | Loope (1985) | 442 | 33.5 | 2 | Nuccio and Condon (1996) |
| 29 | Cedar Mesa Sandstone (b) | Colorado, USA | Mountney and Jagger (2004) | 200 | 11.9 | 2 | Nuccio and Condon (1996) |
| 29 | Cedar Mesa Sandstone (c) | Utah, USA | Mountney (2006a) | 200 | 13.0 | 2 | Nuccio and Condon (1996) |
| 30 | Navajo Sandstone | Utah-Arizona border, USA | Loope and Rowe (2003) | 700 | 30.0 | 2 | Bjerrum and Dorsey (1995) |
| 31 | Entrada Sandstone (a) | Utah, USA | Crabaugh and Kocurek (1993) | 300 | 21.3 | 2 | Nuccio and Roberts (2003) |
| 31 | Entrada Sandstone (b) | New Mexico, USA | Benan and Kocurek (2000) | 300 | 15.0 | 2 | Nuccio and Condon (1996) |
| 31 | Entrada Sandstone (c) | Arizona, USA | Kocurek and Day (2018) | 300 | 26.4 | 2 | Nuccio and Condon (1996) |
| 32 | Big Bear Formation | California, USA | Stewart (2005) | 385 | 8.8* | 1 | Stewart (2005) |
| 33 | Wolfville Formation | Nova Scotia, Canada | Leleu and Hartley (2018) | 833 | 64.7 | 2 | Schlische and Anders (1996) |
| 34 | Page Sandstone (a) | Utah, USA | Jones and Blakey (1997) | 56 | 61.6 | 2 | Bjerrum and Dorsey (1995) |
| 34 | Page Sandstone (b) | Arizona, USA | Kocurek et al. (1991) | 56 | 61.6 | 2 | Bjerrum and Dorsey (1995) |
| 35 | Mancheral Quartzite | India | Chakraborty and | 50 | 13.3* | 2 | Chakraborty and |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | Chaudhuri (1993) | | | | Chaudhuri (1993); Chakraborty (1994); Chaudhuri (2003) |
| 36 | Venkatpur Sandstone | India | Chakrabory (1991) | 70 | 13.3* | 2 | Chakrabory (1991); Chakraborty (2004); Chaudhuri (2003) |
| 37 | Unayzah A | Saudi Arabia | Melvin et al. (2010) | 30 | 2.7 | 1 | Le Nindre et al (2003) |
| 38 | Unayzah (middle member) | Saudi Arabia | Melvin et al. (2010) | 30 | 2.7 | 1 | Le Nindre et al (2003) |
| 39 | Karutola Formation | India | Chakraborty and Sensarma (2008) | 200 | 3.2* | 1 | Chakraborty and Sensarma (2008); Monhanty (2015) |
| 40 | Nepean Formation | Canada | MacNaughton et al. (2002) | 450 | 25.4 | 2 | Miall (1999) |
| 41 | Pedra Pintada Formation | Brazil | Paim and Scherer (2007) | 120 | 10.9* | 2 | Paim and Scherer (2007); Bicca et al. (2013) |
| 42 | Whitworth Formation | Australia | Simpson and Eriksson (1993) | 1325 | 54.6 | 2 | Palu et al. (2018) |
| 43 | Rodjeberg Formation | Greenland | Olsen and Larsen (1993) | 1100 | 98.0 | 2 | Gautier et al. (2011) |
| 44 | Snehvide Formation | Greenland | Olsen and Larsen (1993) | 1100 | 98.0 | 2 | Gautier et al. (2011) |
| 45 | Sofia Sund Formation | Greenland | Olsen and Larsen (1993) | 1100 | 145.5 | 3 | Gautier et al. (2011) |
| 46 | Alinya Formation | Australia | Zang (1995) | 750 | 51.0 | 2 | Lindsay (2002) and references therein |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 47 | Bakoye Formation | Africa | Deynoux et al. (1989) | 125 | 5.0 | 1 | Bronner et al. (1980) |
| 48 | Galesville Member | Wisconsin, USA | Dott et al. (1986) | 50 | 24.6 | 2 | Howell and Van der Pluijm (1999) |
| 49 | Kilmurry Formation | Ireland | Morrisey et al. (2012) | 1000 | 166.3 | 3 | Williams (2000) |
| 50 | Lower Dala Sandstone | Sweden | Pulvertaft (1985) | 175 | 2.3* | 1 | Pulvertaft (1985) |
| 51 | Pewamo Formation | Michigan, USA | Benison et al. (2011) | 25 | 26.3 | 2 | Cercone (1984) |
| 52 | Shikaoda Formation | India | Chakraborty and Chakraborty (2001) | 100 | 3.7* | 1 | McMenamin et al. (1983); Ray (2006) |
| 53 | St. Peter Sandstone | Wisconsin, USA | Dott et al. (1986) | 213 | 10.8 | 2 | Armitage and Allen (2010) and references therein |
| 54 | Wonewoc Formation | Wisconsin, USA | Dott et al. (1986) | 50 | 24.6 | 2 | Howell and Van der Pluijm (1999) |
| 55 | Varzinyha | Brazil | Paim and Scherer (2007) | 200 | 10.9* | 2 | Paim and Scherer (2007); Bicca et al. (2013) |

Table 1

| **Aeolian Architectural Element Types** | |
|---|---|
| Dune-set elements | Dune-sets form the fundamental unit of deposition of an aeolian sand dune; dune-sets are formed of packages of cross-strata (Sorby, 1859; Allen, 1963; Rubin and Hunter 1982; Chrintz and Clemmensen, 1993); if dune sets migrate over each other, cross-stratified packages are truncated, delineating sets that are bounded by erosional surfaces (Brookfield, 1977; Kocurek, 1996). |
| Sandsheet elements | Sandsheet deposits are low-relief accumulations of aeolian sediment in areas where dunes are generally absent (Nielsen and Kocurek, 1986; Brookfield, 1992; Rodríguez-López et al., 2012); sandsheets can also comprise low-relief bedforms such as zibars. |

| | |
|---|---|
| Interdune elements | Interdune deposits are formed in the low-relief, flat, or gently sloping areas between dunes; neighboring dunes are separated by interdunes (Hummel and Kocurek, 1984). |
| Dry interdune elements | Dry interdunes are characterized by deposits that accumulate on a substrate where the water table is well below the ground surface, such that sedimentation is not controlled by and is largely not influenced by the effects of moisture (Fryberger et al., 1990). |
| Damp interdune elements | Damp interdunes are characterized by deposits that accumulate on a substrate where the water table is close to the ground surface, such that sedimentation is influenced by the presence of moisture (Fryberger et al., 1988; Lancaster and Teller, 1988; Kocurek et al., 1992). |
| Wet interdune elements | Wet interdunes are characterized by deposits that accumulate on a substrate where the water table is elevated above the ground surface such that the interdune is episodically or continuously flooded with water (e.g. Kocurek, 1981; Hummel and Kocurek, 1984; Pulvertaft, 1985; Garcia-Hidalgo et al., 2002; Granja et al., 2008; Mountney and Russell, 2004, 2009; Mountney, 2012) |
| **Aeolian Facies Element Types** | |
| Wind-ripple bearing strata | Wind-ripple lamination forms when wind-blown, saltating grains strike sand-grains obliquely and propel other grains forward (Bagnold, 1941; Hunter, 1977). The foreset laminae of wind-ripple strata are occasionally preserved (rippleform laminae), however, the internal laminae of wind-ripple strata are often indistinguishable due to grain size uniformity (translatent wind-ripple stratification; Hunter, 1977). Wind-ripple strata can occur in a variety of aeolian settings and are especially common in dune-plinth environments, but can also occur on dune lee slopes (Hunter, 1977; Hunter, 1981). Wind-ripple strata can intercalate with packages of grainflow, grainfall and plane-bed strata to various degrees; all facies containing wind-ripple strata are grouped into this category. |
| Grainflow/ Grainfall strata | Grainflow strata form where a dune slipface undergoes gravitational collapse (Hunter, 1977; Bristow and Mountney, 2013). Grainflow deposits are typically erosionally based and are devoid of internal structure, forming discrete tongues or wide sheets of inclined strata on the lee-slope of dunes, which wedge-out towards the base of the dune. Individual grainflow strata may be indistinguishable, resulting in amalgamated grainflow units (Howell and Mountney, 2001). Grainfall strata are gravity-driven deposits that occur when the wind transports saltating clouds of grains beyond a dune brink; grains settle onto the upper portions of lee slopes as wind transport capacities reduce in the lee-side depressions (Nickling et al., 2002). Grainfall laminae are typically thin (<1 mm), drape existing topography, else may have a wedge-shaped geometry; grainfall lamination is generally composed of sand and silt or (rarely) clay sizes grains (Hunter, 1977). Grainflow and grainfall strata commonly intercalate on dune lee slopes. |

| | |
|---|---|
| **Non-Aeolian Element Types** | |
| Fluvial/Alluvial | Deposits arising from or relating to the action of rivers/streams and sediment gravity-flow processes (cf. Melton, 1965). |
| Marine | Deposits arising from or relating to accumulation in marine environments. |
| Lacustrine | Deposits arising from or relating to accumulation in perennial lakes. |
| Sabkha/Playa | Sabkhas and playa lakes describe low-relief flats where evaporites, and in some cases carbonates, accumulate. The terms sabkha and playa lake were originally used to describe coastal and inland settings, respectively (Evans, et al., 1964; Purser and Evans, 1973); however, the terms are now commonly used interchangeably. |
| Paleosol | Preserved fossil soil. |
| Volcanic | Deposits relating to intrusive (e.g., sills and dykes) or extrusive (e.g., lava flows) volcanic activity and any other volcaniclastic deposits. |
| **Surface Types** | |
| Supersurface | Surfaces resulting from the cessation of Aeolian accumulation; occurs where the sediment budget switches from positive to negative (cannibalization of aeolian system) or neutral (zero angle of climb), resulting in deflation (***deflationary supersurface***) or bypass (***bypass supersurface***) of the Aeolian system, respectively. Supersurfaces are also generated by changes in depositional environment, such as transition from aeolian to fluvial, or aeolian to marine deposition (e.g., Glennie and Buller, 1983; Chan and Kocurek, 1988). |
| Unstabilized Supersurface | Supersurfaces ***not*** associated with sedimentary features indicative of long-term substrate stabilization. |
| Stabilized Supersurface | Supersurfaces associated with sedimentary features indicative of long-term substrate stabilization, including rhizoliths, deflationary pebble lags and chemical cementation (Loope, 1985; Loope, 1988; Kocurek, 1991; Scherer and Lavina, 2006; Basilici et al., 2009; Dal' Bo et al., 2010). |
| Wet-type supersurface | Supersurface associated with deflation down to the water-table (also known as a Stokes surface). Wet-type supersurfaces may be associated with aqueous inundation by a non-aeolian source (e.g., fluvial/marine deposits). |
| Damp-type supersurface | Supersurface associated with bypass/deflation; the level of the water table is interacting with the surface. |
| Dry-type supersurface | Supersurface associated with bypass/deflation; the level of the water table is significantly below the surface. |
| Interdune migration surface | Bounding surfaces resulting from the migration and downwind climbing of interbedded dune and interdune elements (Kocurek, 1981). |

Table 2

| **Thickness of Aeolian Succession (Case Study)** | | | |
|---|---|---|---|
| Subsidence Rate | Slow (Group 1) | Moderate (Group 2) | Rapid (Group 3) |
| Mean | 200.01 | 368.60 | 916.00 |

| | | | |
|---|---|---|---|
| Median | 150.00 | 221.50 | 1000.00 |
| Standard Deviation | 171.23 | 356.29 | 633.66 |
| Observations | 16 | 34 | 5 |
| ANOVA P-Value | <0.01 | | |
| **Thickness of Aeolian Architectural Elements** | | | |
| Subsidence Rate | Slow (Group 1) | Moderate (Group 2) | Rapid (Group 3) |
| Mean | 2.68 | 3.58 | 8.68 |
| Median | 1.00 | 2.00 | 5.00 |
| Standard Deviation | 11.74 | 5.23 | 11.38 |
| Observations | 695 | 1349 | 387 |
| ANOVA P-Value | <0.01 | | |
| **Thickness of Non-Aeolian Architectural Elements** | | | |
| Subsidence Rate | Slow (Group 1) | Moderate (Group 2) | Rapid (Group 3) |
| Mean | 3.40 | 2.96 | 3.77 |
| Median | 1.35 | 1.20 | 0.25 |
| Standard Deviation | 9.33 | 5.06 | 15.77 |
| Observations | 314 | 891 | 143 |
| ANOVA P-Value | 0.10 | | |
| **Thickness of Dune-Set Elements** | | | |
| Subsidence Rate | Slow (Group 1) | Moderate (Group 2) | Rapid (Group 3) |
| Mean | 2.09 | 4.57 | 9.66 |
| Median | 1.50 | 2.50 | 6.00 |
| Standard Deviation | 2.14 | 5.90 | 11.65 |
| Observations | 402 | 916 | 346 |
| ANOVA P-Value | <0.01 | | |
| **Length of Dune-Set Elements** | | | |
| Subsidence Rate | Slow (Group 1) | Moderate (Group 2) | Rapid (Group 3) |
| Mean | 47.04 | 153.07 | 232.83 |
| Median | 14.00 | 60.00 | 120.00 |
| Standard Deviation | 61.30 | 305.37 | 389.47 |
| Observations | 178 | 382 | 91 |
| ANOVA P-Value | <0.01 | | |
| **Thickness of Sandsheet Elements** | | | |
| Subsidence Rate | Slow (Group 1) | Moderate (Group 2) | Rapid (Group 3) |
| Mean | 2.71 | 2.51 | 1.69 |
| Median | 0.28 | 1.50 | 0.75 |
| Standard Deviation | 10.93 | 3.48 | 2.23 |
| Observations | 172 | 372 | 4 |
| ANOVA P-Value | 0.92 | | |

| Thickness of All Interdune Elements | | | |
|---|---|---|---|
| Subsidence Rate | Slow (Group 1) | Moderate (Group 2) | Rapid (Group 3) |
| Mean | 0.60 | 1.12 | 0.26 |
| Median | 0.25 | 0.50 | 0.20 |
| Standard Deviation | 1.09 | 2.10 | 0.21 |
| Observations | 115 | 148 | 37 |
| ANOVA P-Value | <0.01 | | |
| **Thickness of Wet Interdune Elements Only** | | | |
| Subsidence Rate | Slow (Group 1) | Moderate (Group 2) | Rapid (Group 3) |
| Mean | 0.44 | 1.05 | 0.25 |
| Median | 0.25 | 0.30 | 0.15 |
| Standard Deviation | 0.40 | 2.10 | 0.21 |
| Observations | 37 | 50 | 34 |
| ANOVA P-Value | 0.02 | | |
| **Thickness of Damp Interdune Elements Only** | | | |
| Subsidence Rate | Slow (Group 1) | Moderate (Group 2) | Rapid (Group 3) |
| Mean | 0.69 | 0.80 | 0.27 |
| Median | 0.28 | 0.50 | 0.20 |
| Standard Deviation | 1.36 | 1.10 | 0.12 |
| Observations | 70 | 48 | 3 |
| ANOVA P-Value | 0.7 | | |
| **Thickness of Dry Interdune Elements Only** | | | |
| Subsidence Rate | Slow (Group 1) | Moderate (Group 2) | Rapid (Group 3) |
| Mean | 0.72 | 1.35 | - |
| Median | 0.5 | 02 | - |
| Standard Deviation | 0.48 | 2.58 | - |
| Observations | 5 | 44 | - |
| ANOVA P-Value | 0.59 | | |
| **Angle of Climb** | | | |
| Subsidence Rate | Slow (Group 1) | Moderate (Group 2) | Rapid (Group 3) |
| Mean | 0.39 | 0.54 | 1.7 |
| Median | 0.39 | 0.45 | 1.12 |
| Standard Deviation | 0.40 | 0.50 | 1.21 |
| Observations | 2 | 14 | 11 |
| ANOVA P-Value | <0.01 | | |
| **Dune Wavelength** | | | |
| Subsidence Rate | Slow (Group 1) | Moderate (Group 2) | Rapid (Group 3) |
| Mean | 140.00 | 610.36 | 780.00 |
| Median | 150.00 | 900.00 | 700.00 |

| | | | |
|---|---|---|---|
| Standard Deviation | 65.57 | 505.39 | 170.59 |
| Observations | 3 | 21 | 9 |
| ANOVA P-Value | 0.09 | | |
| **Interdune Migration Surface Length** | | | |
| Subsidence Rate | Slow (Group 1) | Moderate (Group 2) | Rapid (Group 3) |
| Mean | 64.77 | 158.31 | 255.74 |
| Median | 10.00 | 55.00 | 200.00 |
| Standard Deviation | 163.24 | 350.46 | 201.51 |
| Observations | 23 | 152 | 82 |
| ANOVA P-Value | 0.01 | | |

Table 3